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THE MECHANISMS BY WHICH FABRICS STABILIZE AGGREGATE LAYERS ON SOFT SUBGRADES

by

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Final Report

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The U. S. Army Engineer Waterways Experiment Station (WES) conducted a series of traffic tests on various pavement systems over a soft clay subgrade. A loaded truck was driven repeatedly in the same wheelpath over sections consisting of 14 in. of granular base underlain by very soft clay. Two sections contained a layer of fabric between the base and the subgrade and one control section had no fabric or other separators. The two sections containing fabric and the control section are compared in detail. The general (Continued)

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20. ABSTRACT (Continued).

behavior of fabric in a pavement system is discussed. A method of analysis of the behavior of fabric in a pavement system is presented and used on the two fabric sections. Conclusions are drawn regarding the test series, the use of a fabric layer in pavements in general, the state of the art in pavement design using fabric inner layers, and requirements for future testing.

PREFACE

The investigation reported herein was sponsored by the Office, Chief of Engineers (OCE), U. S. Army, as part of Project 4A161102AT22, Task 02, Work Unit 008, "Effect of Horizontal Fiber Layers in Pavement Systems." This work was performed for the U. S. Army Engineer Waterways Experiment Station (WES) under Contract No. DACA39-77-M-0257 by Dr. E. J. Barenberg and Mr. T. C. Kinney, consulting engineers, Champaign, Ill.

WES personnel directly concerned with this project were Messrs. J. P. Sale, Chief, Geotechnical Laboratory (GL); R. G. Ahlvin, Assistant Chief, GL; H. H. Ulery, Jr., Chief, Pavement Design Division; and D. M. Ladd, Chief, Design Criteria Branch. The OCE Technical Monitor for this project was Mr. S. S. Gillespie.

Director of WES during the conduct of this investigation was COL J. L. Cannon, CE. Technical Director was Mr. F. R. Brown.

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CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
cubic inches	16.38706	cubic centimetres
feet	0.3048	metres
inches	25.4	millimetres
ounches (mass) per square yard	33.90575	grams per square metre
pounds (force) per inch	175.1268	newtons per metre
pounds (force) per square inch	6894.757	pascals
pounds (mass)	0.4535924	kilograms
square inches	6.4516	square centimetres
tons (mass)	907.1847	kilograms

INTRODUCTION

In late 1976 and early 1977 the Waterways Experiment Station (WES) conducted a series of full-scale tests to evaluate several techniques of constructing bridge approaches over soft subgrades. Two of the test sections consisted of fabric covered by crushed rock over a soft grade. Both of these test sections performed considerably better than the control section which consisted only of crushed rock over the soft subgrade. The results of the study were presented in Reference 1.

The purpose of this report is to explain qualitatively the mechanisms involved that make fabric improve the section performance and to quantify as far as possible the results obtained in the tests. Test data on fabric reinforced sections are scarce, and of very limited extent and applicability. Thereotical developments are likewise lacking. The WES study provides much valuable information which leads to some interesting general conclusions.

The first part of this report covers the general mechanisms by which a fabric changes the behavior of the pavement system, and the second part deals with an analysis of the WES test data. General conclusions are given and quantitative information is provided for the data reported. Included in this part are some of the boundary conditions that can be used with the information in Part I to help develop quantitative analysis of the fabric influence on the pavement section. The last part of the report presents some guidelines of desired information from future test programs, along with the general conclusions from this program.

GENERAL ASPECTS OF FABRIC BEHAVIOR IN PAVEMENT SYSTEMS

Fabric performs two major functions in a pavement system. The first is to separate the subgrade from the base materials, and the second is to cause a redistribution of stresses within the mass. These will be discussed below.

Separation

Without a fabric, repeated loading can cause mixing of the subgrade and base at the interface. A relatively small amount of fine grained soil, often as little as 5 to 10 percent, can significantly reduce the critical properties of a granular base. If the intermixing is only to a limited depth it has the effect of reducing the thickness of the granular base.

Blending of the granular material comes about through a combination of the granular material moving down due to a grain by grain bearing capacity failure of the subgrade soil, and the subgrade being squeezed up through voids between the grains or being carried up by water during pumping. All fabrics with small pores will retard this mixing action, hence preserving the full depth of base material to transfer the load to the subgrade.

Stress Redistribution

The interactions between the fabric and other layers of the pavement system are extremely complex. There are three basic mechanisms by which fabrics can change the response characterics of a pavement. The first mechanism involves the normal stress on the fabric. When the subgrade-base interface is deformed, the fabric is put into tension. This tension causes normal stresses on the soil as the fabric curves over the surface. These stresses tend to spread the load.

The second mechanism involves a change in the material properties,

particularly of the granular material, by changing the stresses in that material. A slight change in the minimum principal stress in a granular material when the minimum principal stress is near zero or in tensile strain can have a dramatic effect on the material properties. Such a change in material properties will affect the rutting and will also cause further changes in the stresses within the pavement system.

The third mechanism can be likened to that of tensile reinforcement in concrete. The tension member at the bottom of the granular layer allows the layer to carry some moment, thereby causing a slab-like action which redistributes the stresses and stiffens the pavement system.

Each of these aspects will be discussed below. All of the discussions to follow are based on large deflections and a single wheel path centered in the rut.

Normal Stress on the Fabric

When a rut is formed, the base-subgrade interface is lengthened, stretching the fabric and putting it into tension. When the fabric is stretched over a curved surface, it applies a normal force on the material on the inside of the curved surface according to the following equation:

$$p_n = \frac{T}{r}$$

where: p_n = Normal pressure on material due to fabric.

T = Tensile force per unit length in the fabric.

r = Radius of curvature.

This force is upward at the outside edges of the tire and downward over the heaved portion of the soil outside the rut. The net effect is to "lift" the tire and redistribute this load to the heaved portions outside the rut. This concept is presented graphically in Figure 1. This effect alone

probably does not significantly reduce the magnitude of the peak vertical stress on the subgrade, but it does spread out the pressure near the edge of the loaded area, in effect putting a surcharge on the subgrade outside the loaded area.

Changed Material Properties

Directly under the wheel load the granular materials at the base-subgrade interface tend to move laterally. Without a fabric in the system the horizontal stress in the granular layer drops to near zero when the system is loaded. The inclusion of fabric at the interface provides a restraint to the lateral movement thereby producing a slight compressive horizontal stress in the granular base layer.

This increase in horizontal stress in the granular layer has two effects. The first effect is to increase slightly the elastic modulus of the material. This stiffens the granular material thus allowing it to distribute the load over a wider area of the softer subgrade.

The second effect is to decrease the permanent deformation potential of the granular material. Under repeated loads, granular materials deform permanently with each load application. The amount of permanent deformation is a function of the deviator stress and the principal stress ratio in the granular material. Changing the minimum principal stress from near zero to a value only slightly higher will drastically decrease the principal stress ratio and greatly reduce the amount of permanent deformation per load application in the granular layer.

Prestressed Reinforced Concrete Slab Effect

The granular base and fabric act together in much the same manner as a prestressed reinforced concrete slab. The fabric acts as a tension member

to the extent that the tension is caused by shear forces against the granular base. These shear forces are considerable beneath the wheel area, but much smaller elsewhere.

When the soil is loaded, there is movement under the load causing tension in the fabric and possible slippage between the granular base and the fabric. Upon unloading the fabric contracts, resulting in a pre-stressing effect of the granular material which was directly under the loaded area. Since the granular base can now take moment, there will be a redistribution of stresses within the mass resulting in a spreading of the load on the subgrade.

REVIEW OF WES DATA

The test data shown in Reference 1 were carefully reviewed in an attempt to verify or disprove the mechanisms of fabric support discussed in the previous section. First, the data were reviewed from a general standpoint to determine any fundamental differences in the various test sections; then calculations were made to quantify, in so far as possible, the effect of the fabric on the system. Preceding the analysis is a brief description of the WES test section.

Test Section Description

The following description of the test section summarizes and augments that given in Reference 1. It deals only with the three items under consideration in this report and only with those details necessary for the discussions herein. For further detail refer to Reference 1.

Each test item was placed in an excavation 20 feet wide and 24 inches deep, which was filled with Buckshot clay (CH, LL of 68%, PL or 23%) compacted at a water content of between 35 and 37 percent giving an in-situ CBR of between 1.5 and 2.3. The upper ten inches were then remixed with water added and recompacted at a water content of between 38 to 40 percent, to produce in-situ CBR values of from 0.7 to 1.0. In general, the data (Table 2, Reference 1) indicate that the subgrade material in the west wheel path was slightly softer than the east.

Item 5, the control test section, was then covered with 14 inches of crushed rock. Item 6 had a layer of polyester fabric between the clay and 14 inches of crushed rock. Item 7 had a layer of neoprene coated nylon fabric between the clay and 14 inches of crushed rock. The average properties for these two fabrics are shown below.

Average Fabric Properties

Item 5

Bidim (spunbound, needlepunches, polyester, non-woven)
Width 166 inches
Length 30 feet
Weight 12 oz/sq yd
Elongation at failure 58%
Breaking strength 280 lb/in.

Item 6

T-16 (neoprene-coated, one ply, woven, nylon)
Width 176 inches
Length 30 feet
Weight 18.5 oz/sq yd
Elongation at failure 31%
Breaking strength 435 lb/in.

Loads were then applied in four separate series using a five ton, tandem-axle, dual wheel, military dump truck. The wheel configuration and loading for each series are shown on Figure 2. The loading schedule on the system was as follows:

Series	No. of Passes	Approx. Load on Tandem Axle-lbs.
1	500	25,000
2	400	35,000
3	300	47,000
4	500	55,000

The truck was driven forward and then backed over the test sections always keeping in the same wheel path.

General Observations

The general observations are divided into two groups: 1) those involving the rut depth as a function of loading, and 2) those involving the shape of the rut, movement of material under the wheel loads and volume changes in pavement materials. Each is discussed below. The data presented in Reference 1 are sparse and of marginal accuracy for the relationships that are developed herein. While it is believed that the general trends presented are realistic, the absolute values should be viewed with caution.

Rut Depth Versus Loading

The rut depth discussed in Reference 1 is a total effective rut depth taken as the distance from the deepest portion of the rut to the highest point on the heaved material. The item was considered to have failed when the truck differential dragged. This definition of rutting and failure has considerable practical significance, but adds an additional variable to the analysis of the data. Thus, for this analysis, rut depth was redefined as the average depth of the rut below the original surface elevation over the width of the wheel and is referred to herein as the adjusted rut depth.

Reference 1 presents the data in terms of equivalent coverages of a standard wheel loading. This concept has some merit in design, but for analysis again clouds the picture with unnecessary information and assumptions which may mask significant features of the response. Every pavement system behaves differently to different load levels and load configurations as well as to stress history. This is especially true of pavement systems containing fabric, since the fabric is non-elastic, creep sensitive and may slip relative to the soil or the granular material under some conditions.

A plot of the adjusted rut depth versus number of coverages (WES definition) is shown in Figure 3. Although the data are sketchy, several interesting trends emerge. First there seems to be a seating rut depth which must be attained before the effects of the fabric can be mobilized. It can be speculated that the first pass created a rut depth on the order of 0.5 to 1.0 inches, and without fabric, each successive pass created a successively deeper rut until failure. The shape of the load coverage curve for the section without fabric is concave upwards. With the polyester

fabric each coverage caused significant permanent increase in rut depth until a seating rut depth was attained. This was on the order of three to four inches deep, beyond which each coverage caused a successively lower level of rutting. With the T-16 fabric the corresponding break point occurs at a rut depth of approximately one and one-half to two inches. The ratio of the seating rut depths for the two fabrics is nearly inversely proportional to the fabric stiffness.

The second significant feature is the amount of rutting per coverage after the seating rut depth has been passed. At 2500 coverages the polyester fabric section was rutting at the rate of about 0.0015 inch per coverage while the rate in the T-16 fabric section was only about 0.0001 inch per coverage. With the limited data available one can speculate that the amount of rutting per coverage appears to be inversely proportional to the fabric stiffness.

When the adjusted rut depths were plotted against number of passes (Figure 4), the possibility of an entirely different interpretation appears. The phenomenon of a seating rut depth can still be seen, but it appears that below the critical load each successive pass creates less rutting than the one before, resulting in a curve which is concave downwards. Above this critical load, however, each pass may create more rutting than the one previous, and the curve is concave upwards.

Rut-Size, Shape and Volume Relationships

The profile data shown on plates 7, 8 and 9 of Reference 1 were replotted to a larger natural scale. Smooth curves were then drawn through the data points, tempered by the expected shape. Various dimensions and volumes were then measured from the original undeformed profiles. The more meaningful measurements are shown in Tables 1 and 2. These measurements,

coupled with the fact that the T-16 fabric is considerably stiffer than the polyester fabric, yield the following conclusions:

1. In all sections the west rut is larger than the east rut.

Since this effect is demonstrated throughout all seven items, it is very unlikely that it is caused by nonuniformity in the base or reinforcing materials. The left wheel load was generally slightly heavier than the right (Figure 2). On the assumption that the truck was headed north this could contribute to the nonuniformity; however this is probably not the sole cause. Most likely, upon reworking of the top ten inches of the subgrade, the subgrade soil on the west side became slightly wetter, and hence weaker. The report indicates that the measured in-place CBR was between 0.7 and 1.0. A CBR spread of only 0.3 indicates careful workmanship in the test bed; however it should be noted that a CBR of 1 is 43% higher than a CBR of 0.7. The construction sequence is such that one might expect the strength variation to be less in the longitudinal direction than the transverse direction. The data shown on Table 2 of Reference 1 indicates that this might be the case.

2. At failure, as redefined here, the stiffer fabric yields a deeper rut.

This conclusion is interesting because it shows that a failure criterion cannot be defined by rut depth alone. It must consider the shape of the rut as well as the shape of the bulge between the wheel paths. The fabric properties seem to effect these shapes.

3. For a given rut depth the stiffer fabric tends to produce a wider rut.

This indicates that the fabric does cause the stress to be distributed outward. Whether this is caused directly by the fabric pressure exerted on the subgrade in the concave downward portions of the rut or by an increased stiffness of the granular material caused by tensile reinforcement is not clear. The data indicate that the wider rut is not solely a function of more wander due to the increased number of loads (Table 2).

4. At failure there is a larger decrease in volume of granular materials in the section with the stiffer fabric.

This conclusion may not be significant since the section having the stiffer fabric not only had more passes but the truck was also more heavily loaded.

5. There is relatively little change in volume of the subgrade regardless of the fabric used.

> This indicates that the subgrade materials do not densify significantly, and that rutting or deformation in the subgrade is caused by a general flow of soil. The flow is probably greatest immediately under the wheel load indicating that there is lateral movement of the subgrade at the interface even when fabric is present.

6. At failure there is more subgrade movement in the sections with the stiffer fabric.

> If this conclusion is turned around slightly, it forms the basis for an interesting hypothesis. If it is necessary to move more subgrade to reach failure using a stiffer fabric, then it follows that it should take more load repetitions to cause a specified rut depth. The fact that item 7 had a heavier load applied at failure may negate this comment.

7. The use of a stiffer fabric tends to spread out the heave in both the granular base and the subgrade.

> This statement reinforces the one made in conclusion 6. Not only must more material be moved, but the movement occurs farther from the loaded area. Therefore not only should it take more repetitions to move more material, but the effect of each repetition is less, because the effects are acting over an area farther removed from the load.

8. At failure there is more total elongation of the subgrade-base interface in the section having the stiffest fabric.

> More elongation of the subgrade-base interface should indicate more fabric strain and hence higher fabric forces. The larger strain is amplified by the stiffness of the fabric to further improve the characteristics.

<u>Quantitative Analysis</u>

There are sufficient data available from the WES test sections to estimate quantitatively some of the effects of the fabric on the pavement response. The general procedures for a simplified analysis are described below, followed by specific calculations on each test section.

General Procedure

The previous section described the following three mechanisms by which fabric improves the pavement system:

1. Normal stress on fabric.
2. Changed material properties.
3. Prestressed reinforced concrete slab effect.

The first is probably the most significant in sections with large deformations. It can be evaluated with reasonable accuracy given the deformed shape and tension in the fabric. Evaluation of mechanisms two and three above requires detailed knowledge of the direction and magnitude of the shear stresses on both sides of the fabric, detailed stress distribution information within the soil, and detailed soil property data. Any attempt to evaluate these two mechanisms from the available data would be futile. Therefore only the first mechanism will be discussed in detail here.

The deformed shape of the fabric was measured at the end of testing for each section in its unloaded state. It is reasonable to assume that under load the fabric has the same general shape but slightly more amplitude than at the end of testing with no load on the system.

The fabric tension cannot be calculated from the data provided. There are, however, reasonable bounding assumptions that can be made regarding the test section behavior which leads to interesting and informative, if not absolute, estimates of the fabric tension. The clearest way to define the bounding conditions and assumed behavior is through a series of cases. Each case presented has a limited number of overriding assumptions. Each case is solved within the framework of these assumptions and is basically a refinement on previous ones, frequently using results obtained from the analysis of the previous case.

CASE I - No Slippage

One boundary condition that could be applied is that there is no slippage between the fabric and the base or subgrade. This assumption would be correct if the shear bond between the soil and the fabric were sufficiently great as to anchor the fabric to the soil. If the fabric were soft or the deformation small, it is not unreasonable to assume that the actual shear bond developed would be high enough to validate the assumption.

Solution for this case requires knowledge of and assumptions as to the stress-strain characteristics of the fabric, the strain in the soil at the base-subgrade interface, and the deformed shape of the fabric under load. Each of these topics are discussed separately below.

Stress-Strain Characteristics of Fabrics - The stress-strain characteristics of fabrics have not been well defined in general. Most fabrics appear to have a non-linear, inelastic and, at least to some extent, creep sensitive load deformation characteristic. There is some indication that there is a limiting stress or strain at which failure will occur regardless of the stress history. This leads to the conclusion that there is a condition of equilibrium that is reached after many cycles of any given load. Figure 6a depicts such a relationship graphically.

The field loading of the fabric is complex. Since there is a very slight increase in rut depth with each pass of the vehicle, it is reasonable to assume that many cycles are applied at approximately each load level. Both the stress and strain may be increasing slightly or remaining approximately constant with each vehicle passage. The result is a stress-strain diagram with peak stress-strain points which resemble the equilibrium points defined previously, and with unloading and reloading responses

which resemble those of the corresponding equilibrium unloading reloading cycle. Figure 6b shows the anticipated fabric response stress-strain relationships. If the elastic rebound of the fabric is less than the decrease in strain in the soil, unloading the fabric will result in a decrease in fabric strain, but without a corresponding compressive stress because of the flexible nature of the fabric.

The first cycle will normally produce an exceptionally high deformation followed by successively smaller deformation increments with succeeding loading-unloading cycles. Therefore the stress in the fabric will probably be relatively high initially and decrease for subsequent cycles.

Deformed Shape of Base-Subgrade Interface - The deformed shape of the base-subgrade interface was measured by means of a test pit at the conclusion of testing for each test item. The details of the measurements were not reported, hence it is not clear whether or not the fabric was in full contact with the subgrade. It is entirely possible that, in the unloaded state, the fabric would recover and span part of the rut, lifting the granular layer off the subgrade in the region of greatest rutting.

The deformed shape reported in Reference 1 is a result of mass movement of the soil due to shear failure and soil compaction. The maximum rate of deepening of the rut recorded is on the order of 0.02 in/cycle, with rates as low as 0.0001 in/cycle recorded. An elastic analysis of this system indicates the development of rut depths at the base-subgrade interface on the order of 0.1 in/cycle, or 50 to 1000 times greater than the recorded plastic deformation.

Strain in Soil at Interface - Movements of a point at the base-subgrade interface are both vertical and horizontal. The locus of the motion was

measured for the unloaded state, and estimated for the loaded state. The estimated loaded state is shown in Figure 7a.

An axisymmetric finite element analysis assuming stress dependent, elastic materials with no fabric shows that the soil at the interface moves horizontally away from the center of the wheel load. The maximum horizontal movement is about 15% of the maximum vertical movement, and occurs about 14 inches from the centerline of the load. The horizontal movement virtually disappears about 50 inches from the wheel centerline. Assuming the elastic ratio of horizontal to vertical deflection holds, the horizontal deformation can be estimated as shown in Figure 7b.

Based on this assumed horizontal deformation, the total strain at the interface can then be approximated from the following simple geometric relationship:

$$\varepsilon = \frac{1 + \varepsilon_H}{\cos \theta} - 1$$

where: ε = Total strain.

ε_H = Horizontal strain.

θ = Slope of the deformed shape.

Plots of θ, ε_H and ε are shown in Figures 7c, d and e, respectively. The presence of the fabric undoubtedly changes the strain in the soil at the interface, but any attempt to account for this is outside the limits of accuracy of the other assumptions.

<u>Three Dimensional Effect</u> - The conditions without the wheel load applied are two dimensional. The stress at the base-subgrade interface from each set of dual wheel loads could be considered axisymmetric and independent without serious error. When the axisymmetric loads are applied to the two dimensional section, the situation is greatly complicated. As

described previously the elastic deformation under the wheel is small and gradual, giving rise to virtually no fabric elongation parallel to the wheel path. This same deformation applied across the wheel path to an already deformed and tensioned fabric can have a significant effect.

It would be conservative to consider a two dimensional section with a third dimension equal to the length of the tire footprint. A closer approximation would be to use a two dimensional approach, but consider the effective width of the fabric to increase away from the wheels. One such approximation scheme is shown on Figure 8.

Results - The basic analysis was presented in an earlier section and on Figure 1. The deformed shape and radius of curvature of the base-subgrade interface are shown on Figures 9a and b. Tension in the fabric, as shown on Figure 9c, comes from a combination of the base-subgrade interface strain, Figure 7e, and the peak equilibrium stress strain properties of the fabric, Figure 6b. The normal stress on the fabric and the effect of the fabric plane on the system are shown on Figures 9d and e.

The stress normal to the fabric due to strain in the fabric, Figure 6d, indicates a substantial upward or lifting component with no corresponding downward component. The downward force required for equilibrium comes through the very high shear stresses along the sides of the ruts. These high shear stresses counteract those in the soil mass resulting in a decrease in the soil shear stress and a widening of the failure zone.

CASE II - Interior Slippage

The primary assumption in CASE I was that there is sufficient shear resistance available between the soil and the fabric to force the fabric to deform along with the soil. This is not the case if the fabric is sufficiently stiff or the system deformation is sufficiently great so that slippage

will occur. The following analysis allows some slippage near the edges of the wheel load.

Shear Stress Required for No Slippage - *In CASE I the tension in the* fabric was calculated under conditions of full load and no slippage. Figure 10a shows the tension calculated in this manner. A change in tension along the fabric can only be created by shear stresses on the fabric surface. Hence differentiation of the tension with respect to distance gives the shear stress required for the condition of no slippage (see Figure 10b).

Maximum Shear Stress Available - The maximum possible shear stress (τ_{max}) on the fabric is the algebraic sum of the shear stresses on the top and bottom of the fabric. At failure, each may be reasonably represented by the following equation:

$$\tau_{max} = \Sigma C_a + \bar{N} \tan \delta$$

where: C_a = The adhesion between the soil and the fabric.

$\bar{N}$ = The effective normal stress on that side of the fabric.

δ = angle of friction between the soil and the fabric.

The normal force on the top of the fabric can be estimated with reasonable accuracy. The normal force on the bottom of the fabric is equal to that on the top plus or minus the effect of tension in the fabric divided by the radius of curvature as explained earlier. The solution is therefore iterative in nature; however the friction angle between the fabric and the subgrade is relatively small, and an initial estimate will be sufficiently accurate considering the other approximations in the solution. A typical normal force distribution is shown in Figure 10c.

The magnitude of C_a and δ are difficult to estimate without test data.

The grains in a granular material probably will dig into nearly any fabric giving a δ nearly equal to ϕ of the aggregate. The adhesion and friction potential against a fine grained material depend upon the properties of the soil and of the fabric. In the case of the soft Buckshot Clay, a δ angle of 5 to 10° might be reasonable. The adhesion is probably near but less than cohesive strength of the soil with porous fabrics, and considerably less with slick, impermeable fabrics. A typical maximum shear stress distribution is shown in Figure 10d.

Condition for Slippage - The shear stress required for no slippage is compared to the maximum available in Figure 10e. If at any point the maximum shear strength available is less than that required for equilibrium there must be slippage. Figure 10e shows four such places where slippage will occur, namely one along each edge of each rut.

Soil - Fabric Stress, Strain, Deflection Compatibility - The following three basic rules of statics must be satisfied in any soil fabric system.

1. If there is no slippage then the strain in the fabric must equal the strain in the soil.

2. If there is slippage, the shear stress at the fabric soil face will equal the shear strength at the interface.

3. The total longitudinal deflection of the fabric, within the zones of slippage, must be the same for the soil and the fabric unless the ends of the fabric also slip.

By combining these rules in a trial and error procedure, it is possible to determine the amount of slippage at various points in the section, and hence, determine the tension in the fabric.

The total longitudinal deformation of the soil across the section can be easily determined by integrating the strain across the section. The strain shown on Figure 7e was so integrated and is shown on Figure 11a. There is no zero deflection axis since the integration can be started at any point.

The deformation of the fabric can be calculated by integrating the strain in the fabric. Strain in the fabric is related to stress, and the stress is the cumulation of all the shear forces on the fabric starting from one end of the fabric or a point of known tension. If all these relationships are lined up as shown in Figures 11b through 11e, the solution becomes apparent in light of the three concepts outlined above. Unfortunately there does not appear to be a closed form solution for determining the location and width of the area of slippage. Hence it becomes necessary to use an iterative scheme with the following steps:

1. Estimate the location of one end of the slippage zone.
2. Find the shear stresses within the slippage zone, Figure 11b.
3. Calculate the tensile forces in the fabric by integrating the shear stresses from the assumed end of the slippage zone using the known tensile stress in the fabric. The extent of the zone of slippage is determined when the calculated tensile force in the fabric meets an equilibrium position with the known tensile force at the other end of the slippage zone, Figure 11c.
4. Determine the strain throughout the fabric from the fabric stress-strain relationship, Figure 11d.
5. Integrate the fabric strain to get the total fabric elongation and compare with the soil deformation, Figure 11e.
6. If the fabric elongation curve does not coincide with the soil deformation in the areas of no slippage, then repeat steps 1 through 5 with a new slippage zone.

Three special conditions may arise, but are all easily handled in turn. First, the fabric may slip to its end. The end of the fabric is a fixed boundary condition of zero tension and therefore controls the rest of the analysis. Secondly the fabric may show slippage through the entire central zone between the two wheel paths. In this case the fabric can carry tension and have strain, even though the soil appears unstrained and is not slipping against the fabric at one central point in the section. The third

condition arises when the fabric appears to slip through the entire area under the wheel path. If this unlikely event occurs, the boundary condition is that there can be no tension discontinuity in the fabric.

Results - The effect of the fabric on the system considering interior slippage is determined in exactly the same manner as in CASE I. If there is interior slippage, it will tend to decrease the fabric tension in the concave upward portion of the rut and increase the tension in the concave downward portion. This will have the effect of allowing more wheel load to reach the subgrade under the wheel but also to apply more effective surcharge loading on the upward bulging portions of the subgrade.

CASE III - Progressive Slippage

The first two cases are based on the assumption that the fabric does not slip in the unloaded state. When fully loaded, high tensions develop in the fabric requiring high shear stresses between the fabric and other layers. High shear stresses are possible under the wheel load where the normal stresses are high, but upon unloading the potential for high shear stresses decrease, and if the rebound does not reduce the tension in the fabric, then slippage will occur. This case provides the potential cause and effect for progressive slippage which may occur on each unloading cycle.

Unloaded Tension with No Slippage - Each load application produces an increment of resilient deformation, which will be recovered upon unloading, and an increment of plastic deformation which is permanent. As discussed earlier in CASE I the plastic increment is probably much smaller than the resilient increment, and both are much smaller than the final measured rut. If there is no slippage, each load cycle produces an increment of resilient

strain and an increment of plastic strain in the fabric. The fully loaded stress and strain in the fabric would fall on the peak equilibrium repeated loading curve, Figure 6. Unloaded, the tension in the fabric is a function of the rebound strain in the soil and the rebound stress-strain relationships for the fabric. If the rebound strain in the soil is not enough to bring the fabric back to or beyond the zero stress state, then a residual tension exists in the fabric. This concept is shown for the higher strain increments on Figure 6. Each cycle is expected to net a higher residual stress until a slippage stress level is attained or the fabric ruptures.

Unloaded Slippage - Conditions for unloaded slippage to occur are identical to those for the case of interior slippage covered in CASE II. There are however two additional boundary conditions that need to be discussed.

The first boundary condition involves the interaction between the fabric and the soil within the wheel path. Fabric in tension in the concave upwards portion of the wheel path creates an upward normal stress on the base material above the fabric as discussed previously. If this stress is sufficiently large, it will lift the base, creating a void between the fabric and subgrade. There are two significant aspects to this. First the deformed shape in the fabric is changed and second the shear stress between the fabric and subgrade is lost. Since no mention was made in the WES report of the fabric spanning a portion of the rut, it is probably safe to assume that the unloaded fabric shape was substantially the same as the final soil profile. If this is so, it is reasonable to assume that the vertical component of the normal stress, calculated from the relationship between the fabric tension and the radius of curvature, was not significantly greater than the overburden pressure, and in areas where they are

equal, there was little or no shear strength between the fabric and the subgrade.

The second boundary condition relates to the maximum fabric tension between wheel paths. In CASE II it was implied that the high normal stress created by the wheel load would fix the fabric against the soil in the central portion of the wheel path. In the unloaded case the maximum available shear stress in the wheel path may be less than that existing elsewhere, creating a partially free condition rather than a fixed condition. This opens the very real possibility of total slippage of all the fabric upon unloading. The maximum tension in the fabric would therefore be equal to the summation of all the maximum unloaded shear stresses from the end.

Results - The net effect of progressive slippage is to decrease the maximum fabric tension in the wheel path under loaded conditions, and to increase it elsewhere. This tends to decrease the uplift effect of the fabric permitting a greater force from the wheel to the subgrade, and at the same time increases the surcharge effect outside the wheel path.

The amount of progressive slippage that will occur is greatest when:

1. The permanent deformation of the soil is large.
2. The elastic deformation of the soil is small.
3. The loading stress-strain relationship of the fabric is stiff.
4. The rebound stress-strain relationship is soft.

Unfortunately there is not enough information from the WES Test Section to make any realistic estimates of these responses. One bounding estimate can be made if all four factors listed above are assumed to act to extreme; that is, there is complete slippage. Under this condition, the shear stresses on the fabric are the maximum possible as shown on Figure 12a. Note that in

the center portion of the section the fabric elongates more than the soil deforms reversing the sign of the shear stresses between the fabric and the soil. Integrating these shear stresses gives the fabric tension shown in Figure 12b. Since the elastic deformation is small and the rebound stress-strain property of the fabric is soft, there is very little increase in fabric tension during loading. Therefore unloaded tension can be used directly in the analysis of the effect of the fabric presented earlier. Figure 12c shows the result of this analysis.

To determine if this solution is reasonable, the total elongation of the fabric can be compared to the elongation of the base-subgrade interface as explained in CASE II. If the fabric elongation is less than the base-subgrade profile, then slippage must occur. The elongation of the base-subgrade interface determined for CASE II, is shown in Figure 11a. The elongation of the fabric can be determined by integrating the fabric strain. The fabric strain can be reasonably estimated from the fabric tension and the loaded equilibrium stress-strain relationship for the fabric, Figure 6. The strain in the fabric is shown in Figure 12d. The fabric and soil strains are compared on Figure 12e. The possibility of base uplift in the wheel path was ignored in the above analysis, but the effect is probably slight and almost impossible to consider rigorously.

CASE IV - Conditions Not Previously Considered

There are several assumptions made or implied in the previous three cases that have not been considered in detail. Some of them may be significant, but simplified consideration does not appear practical at this time. These conditions are listed below, with no attempt made to consider them in any analysis.

1. Does the base and subgrade move together as a composite system at the interface?

2. Does the fabric cause differential movement in the base and subgrade near the interface?

3. Are the elastic strains proportional to the permanent deformation?

4. Does the presence of the fabric significantly change the distribution of horizontal and vertical motion in the section?

5. How much differential motion between the fabric and the soil is required before full shear stresses are developed?

6. How does the limited thickness of soft subgrade in the WES test sections effect the results?

7. How much do the lower loads used in the earlier items in Sections 6 and 7 effect the response of the system at higher loads (preconditioning)?

Analysis of WES Test Sections

The calculations outlined in the general procedure section were performed for each of the WES test items. For brevity only the calculations for the west rut are shown. The results from the two test items are discussed separately.

Item 6 - "Bidim"

Fabric Stress-Strain Properties - The WES report shows the failure stress and strain for a slightly lighter weight fabric. The failure stress and strain for the fabric used were estimated by assuming that the failure stress is directly proportional to the fabric weight, and that the failure strain is independent of the fabric weight. Assuming this point is valid for the repeated load situation, the equilibrium peak repeated load stress strain relationship was sketched as shown on Figure 13.

Case I - No Slippage - The required calculations are shown in Figures 14 and 15 based on the measured vertical displacements and the estimated fabric properties. The maximum longitudinal strain, Figure 6e, is 13.5 percent,

causing a maximum fabric tension, Figure 15a, of 28 pounds per lineal inch of fabric width. The resulting peak unbalanced normal pressure on the fabric is about 1 psi, as shown in Figure 15c. Comparing this to the normal stress on the subgrade for the section without the fabric, Figure 15d, it is apparent that the calculated effect of the normal stress on the fabric is slight. Unless the estimates of the fabric properties are seriously in error, it appears unlikely that any significant benefit from the Bidim fabric can be ascribed to changes in normal stress transmitted from the base to subgrade caused by fabric tension.

Case II - Interior Slippage - The additional calculations required for CASE II are shown on Figure 16. The following properties were used for calculation of the maximum available shear force:

	Soil		Soil-Fabric	
	c	ϕ	c_a	ϕ
Base	0 psi	33°	0 psi	30°
Subgrade	2	6°	2	5°

Comparing the maximum available shear stress with that obtained by differentiating the fabric tension, Figure 6b, it is apparent that the maximum shear strength is exceeded slightly at only one point. Hence, local slippage cannot be presumed.

Case III - Progressive Slippage - The maximum fabric tension is low and hence progressive slippage is not a consideration.

Conclusion - The primary beneficial effect of the "Bidim" fabric is probably separation of the layers with some minor structural benefit from each of the causes outlined earlier.

Item 7 - "T-76"

Fabric Stress-Strain Properties - The failure stress and strain for the fabric used is given in the WES report. Assuming this relationship applies to the repeated load situation the equilibrium peak repeated load stress-strain relationship was sketched in as shown on Figure 17.

Case I - No Slippage - The required calculations for CASE I are shown on Figures 18 and 19. The peak fabric strain, Figure 18e, is 26%, giving a peak fabric stress, Figure 19a, of 320 pounds per lineal inch of fabric width. The peak unbalanced normal pressure on the fabric, Figure 19c, is 12 psi. Comparing the unbalanced normal pressure with the total normal stress on the fabric, Figure 19d, indicates that the fabric reduces the maximum wheel load stress transmitted to the subgrade by approximately 15 percent, a significant amount.

Case II - Interior Slippage - The additional calculations required for CASE II are shown on Figure 20. The maximum possible shear stress between the fabric and the soil, Figure 20b, was calculated using the following parameters:

	Soil		Soil Fabric	
	c	ϕ	c_a	ϕ
Base	0 psi	33°	0 psi	30°
Subgrade	2	6°	1	5°

Comparing the required shear stress for no slippage and the maximum shear strength available, Figure 20b, it is obvious that slippage will occur on both sides near the edges of the wheel path. While the entire profile is required for solution of the slippage problem because slippage occurs across the centerline of the test section, only the west rut is shown on Figure 20. The net effect is to reduce slightly the upward unbalanced pressure on the

fabric, but to increase the downward unbalanced pressure particularly across the center section of the test section, Figure 20e.

Case III - Progressive Slippage - The calculations necessary for CASE III are shown on Figure 21. The longitudinal deflection compatability between the fabric and the soil, Figure 21d, indicates that this case is not likely for the conditions given and the end will not slip. A slight increase in fabric stiffness or a decrease in maximum shear stress from those assumed could change this conclusion however. It is interesting that the CASE II and CASE III pressure diagrams, Figures 20c and 21b, are very similar. CASE III shows a slightly higher amplitude at each edge of the rut particularly on the outside of the test sections. The increase on the inside exists only because the deflection compatability did not show the reversal in direction of the shear stress which must exist for this case to be valid.

Conclusion - CASE II probably most closely represents the conditions in the test section. The reduction in stress transmitted to the subgrade is about 17 percent at the point of loading. Extending this axisymmetrically for the load and two dimensionally for the fabric, such a reduction might increase to as high as 21 percent. This reduction along with the surcharge effects and the benefits gained from the other two mechanisms of improvement and the effective rut producing load might be decreased by perhaps 30 percent or more.

CONCLUSIONS AND RECOMMENDATIONS

The review and explanation of the results of the WES data contained herein has brought to light a number of interesting conclusions. Some of them pertain to the test results themselves and others relate to the techniques used to analyze the test results. The following comments give guidelines to follow in the design of a soil fabric system as well as suggestions on how to improve the performance of similar tests in the future.

Conclusions Regarding the Fabric Response in the WES Tests

The WES tests effectively demonstrated the following response characteristics of fabric in the test sections.

1. Use of fabric between the soil and the granular base improves the response characteristics of the pavement system therefore increasing its useful life.
2. The T-16 fabric was more beneficial than the Bidim fabric.
3. Even relatively weak fabrics provide some benefits by providing an effective separation barrier between the soft subgrade and the base course materials.
4. Fabrics with a high resistance to deformation produce a change in the stress distribution within the system, effectively spreading the load on the subgrade.
5. The apparent benefits of the fabric may have been exaggerated or reduced due to the very limited thickness of soft subgrade.
6. The apparent benefits of the fabric may have been exaggerated because of the loading sequence as light loads applied to a system before heavy loads tend to improve the response of the system under the heavier loads.
7. The Bidim fabric probably served primarily as a separator in Item 6 with only minor stress redistribution effects.
8. The T-16 fabric also acted as a separator, but also produced an effective decrease in rut producing load on the subgrade, possibly up to as much as 30 percent.

Comments on the Use of Fabric for Bridge Approach Roads Across Soft Ground

Fabric can be effectively used to increase the life of bridge approach type roads across soft soils. The discussions contained in this report lead to several general recommendations regarding such uses.

1. Nearly any fabric (strong enough so it will not tear during construction) will perform the separation function.

2. The stress redistribution function becomes more pronounced as deformation at the base-subgrade interface increases. There may, however, be some small, but significant effects at very low deformations.

3. Once rutting has occurred at the fabric level, all future traffic should follow in the same wheel path. Smoothing the surface will further strengthen the system by raising the wheel load farther off the subgrade; however once smoothed the vehicle should not be allowed to wander significantly out of the original wheel path.

4. Higher modulus fabrics provide the most benefit because the fabric tension is increased at lower deformations. There appears to be an optimum stiffness beyond which no additional benefit will be gained.

5. The non-linear and non-elastic behavior of the fabrics do not appear to detract from the fabric's benefits, but creep does. Fabrics that creep under constant load should be avoided.

6. Tension in the fabric outside the wheel path is determined by the amount of shear resistance available, and the amount of deformation obtained. Ideally the ends of the fabric would be anchored just outside the heaved portion of the rut. If anchorage is not used, the fabric should be wide enough to avoid slippage. Figure 5 graphically demonstrates the relationships between deformation, fabric width and shear stresses on the fabric. It is seen from Figure 5 that narrow fabrics limit the amount of tension available, and that anchors greatly reduce the deformation necessary to develop a given tension.

7. Pretensioned fabric would improve the performance, although it would be difficult to construct.

8. Prestretching a fabric in the direction perpendicular to the wheel path may prove very valuable and practical to increase the tension in the fabric at lower deformations.

9. There is some experimental evidence, Reference 3, that multiple layers of fabric placed within the granular base materials may significantly improve the system response.

Conclusions Regarding the State of the Art in Design and Analysis

No comprehensive scheme has been devised thus far to adequately model the behavior of a soil fabric system. The concepts presented herein, coupled with a finite element approach, could possibly yield reasonable results. The major problems associated with a rigorous analysis are as follows:

1. The problem requires a creep failure model for soil under repetitive loading which has not been developed.
2. Fabric slippage is difficult to model.
3. Large strain elements must be used. Such finite element models have been developed, but are not in common use today.
4. The repetitive loading response of the fabric must be known, and very little work has been done so far on this characteristic of fabrics.
5. A great many repetitive loading cycles would be cost prohibitive. Since the fabric and the soil are stress level and stress history dependent, a method must be devised for short-cutting the process.
6. The problem is three dimensional which today is very costly to analyze. Two dimensional and axisymmetric analysis models can be used to bound the problem, but they are not completely adequate.

There is enough information available today to make large advances in the state of the art in analysis, but a truly rational analysis is probably some time away.

Design is therefore limited to empirical approaches such as in the WES study discussed herein, or in a combined empirical and theoretical approach such as that discussed herein and in Reference 2. Progress is being made, but today there is no adequate method for design of soil-fabric-aggregate systems.

Recommendations for Measurements on Future Full Scale Tests

Ideally a complete time history of all stresses and strains throughout the system would be desirable. This is impossible; hence we must settle

for the minimum amount of information that will define the mechanisms involved. The approach taken by WES in the current study is good; but the following additional information would have greatly increased the value of the test results.

1. Several detailed surface profiles during each series of loading.

2. One test trench at the end of each series and, if possible, one intermediate test trench during testing.

3. Horizontal displacements of the fabric and the side of the fabric. This could easily be done by painting a line on the fabric and embedding an object in the soil immediately above and below the line. This should be done at least every six inches starting at the centerline of the wheel path.

4. Density measurements of the base and subgrade before and after trafficking under the center of the wheel path and in the heaved areas.

5. Elastic deformations at the time the profiles are taken. An elastic deformation profile would be ideal; however the centerline deflections would provide valuable information.

Laboratory tests on the fabric, the soil, and the shearing resistance between the fabric and the soil are also necessary. These tests must be of the repetitive nature to define the system parameters as they exist during loading.

LIST OF REFERENCES

1. Webster, S. L., and Walkins, J. E., "Investigation of Construction Techniques for Tactical Bridge Approach Roads across Soft Ground," Technical Report S-77-1, U. S. Army Engineer Waterways Experiment Station, Feb. 1977.

2. Bender, D., and Barenberg, E. J., "Analysis of Soil-Fabric-Aggregate Systems," Prepared for Celanese Fibers Marketing Company, June 1977.

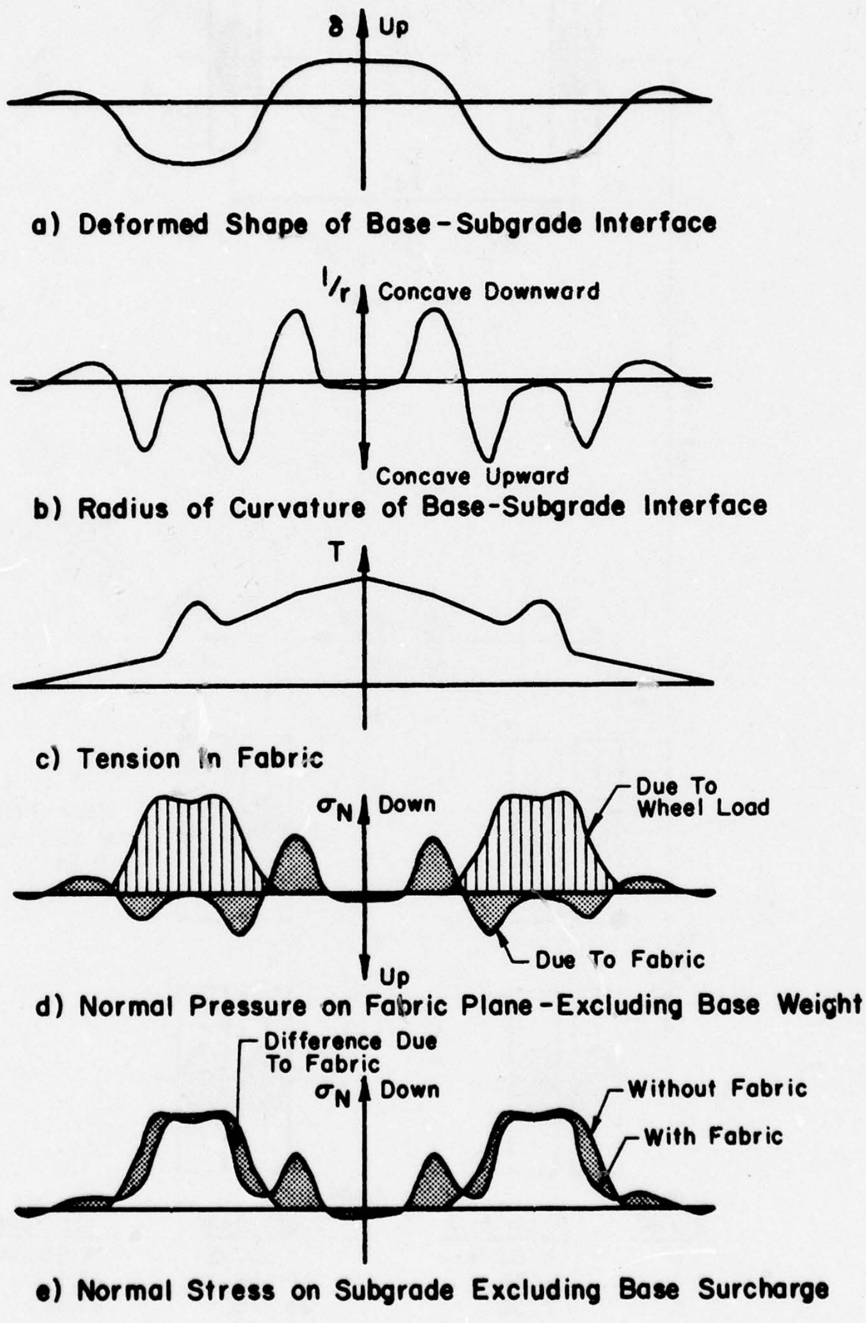
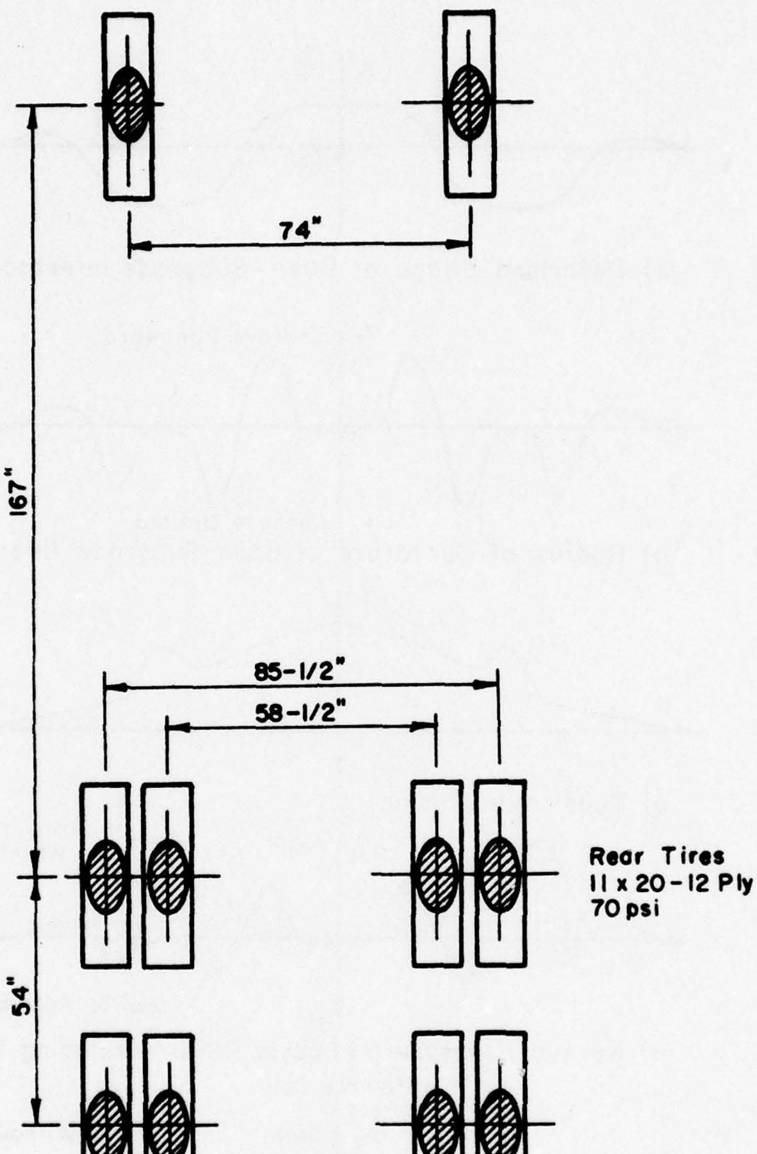


Figure 1. Stress Redistribution Due to Normal Stress on the Fabric.



	Load		
Series	Front Axle	Right Rear	Left Rear
1	8400 lb.	12,500 lb.	12,850 lb.
2	8875	17,650	17,500
3	7050	23,275	23,825
4	7175	27,000	28,225

Figure 2. Wheel Configuration and Loading Sequence.

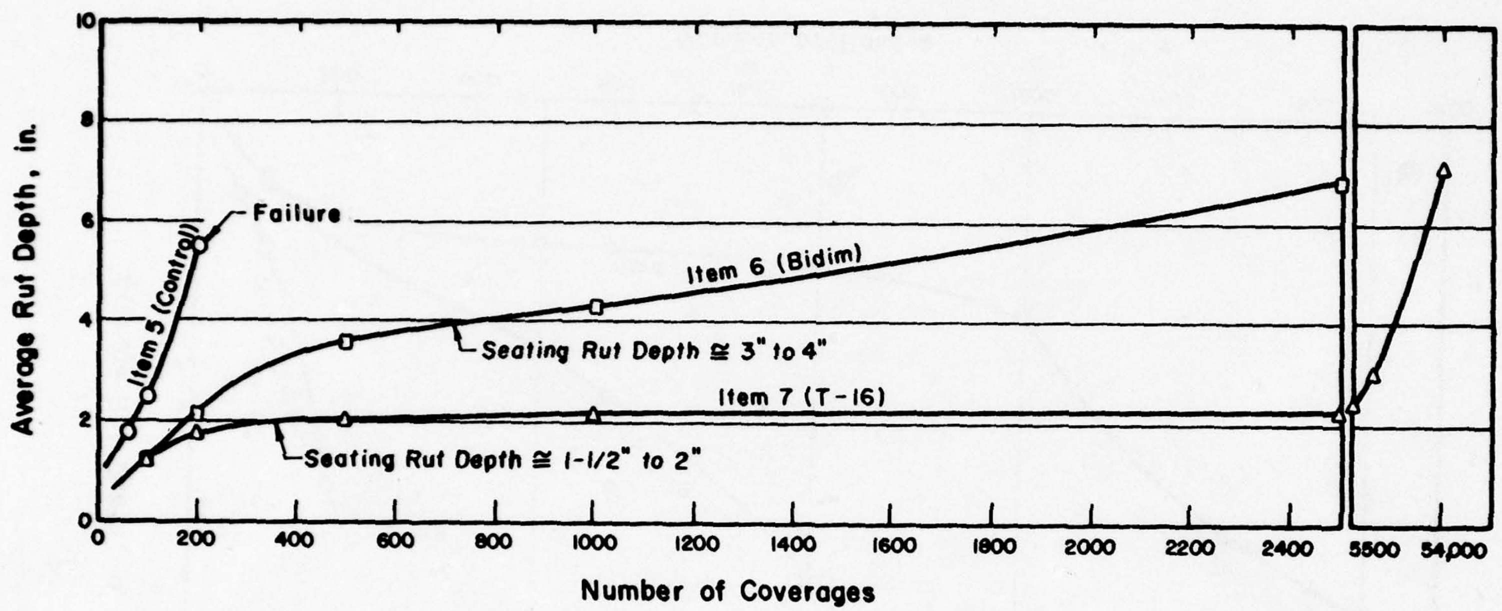
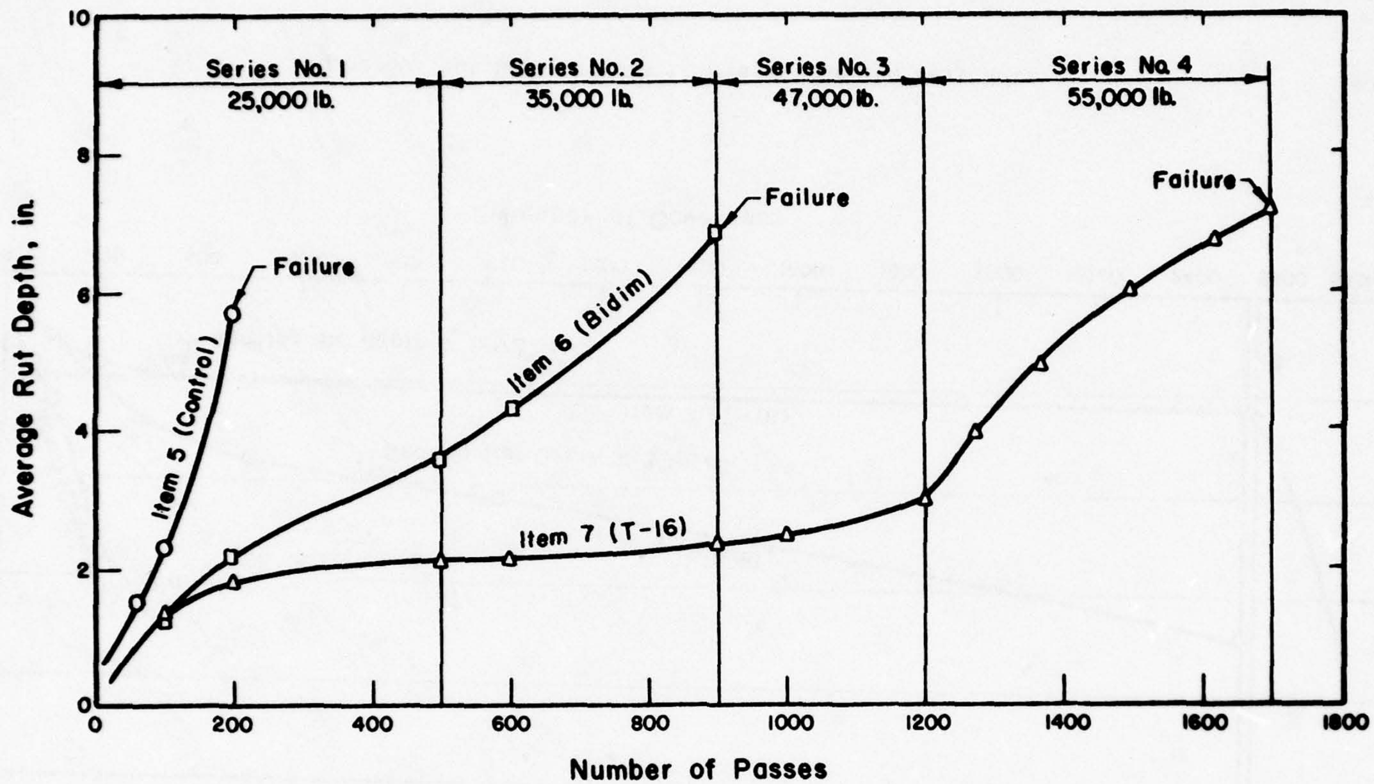


Figure 3. Rut Depth Versus Coverages for the West Rut.



Note: 1. Failure defined by WES as when truck differential dragged.
2. Rut depths shown are average over length of each test item.
3. Data compiled and reported by WES. Data not available for other analysis.

Figure 4. Rut Depth as a Function of Vehicle Passes for West Wheel Path.

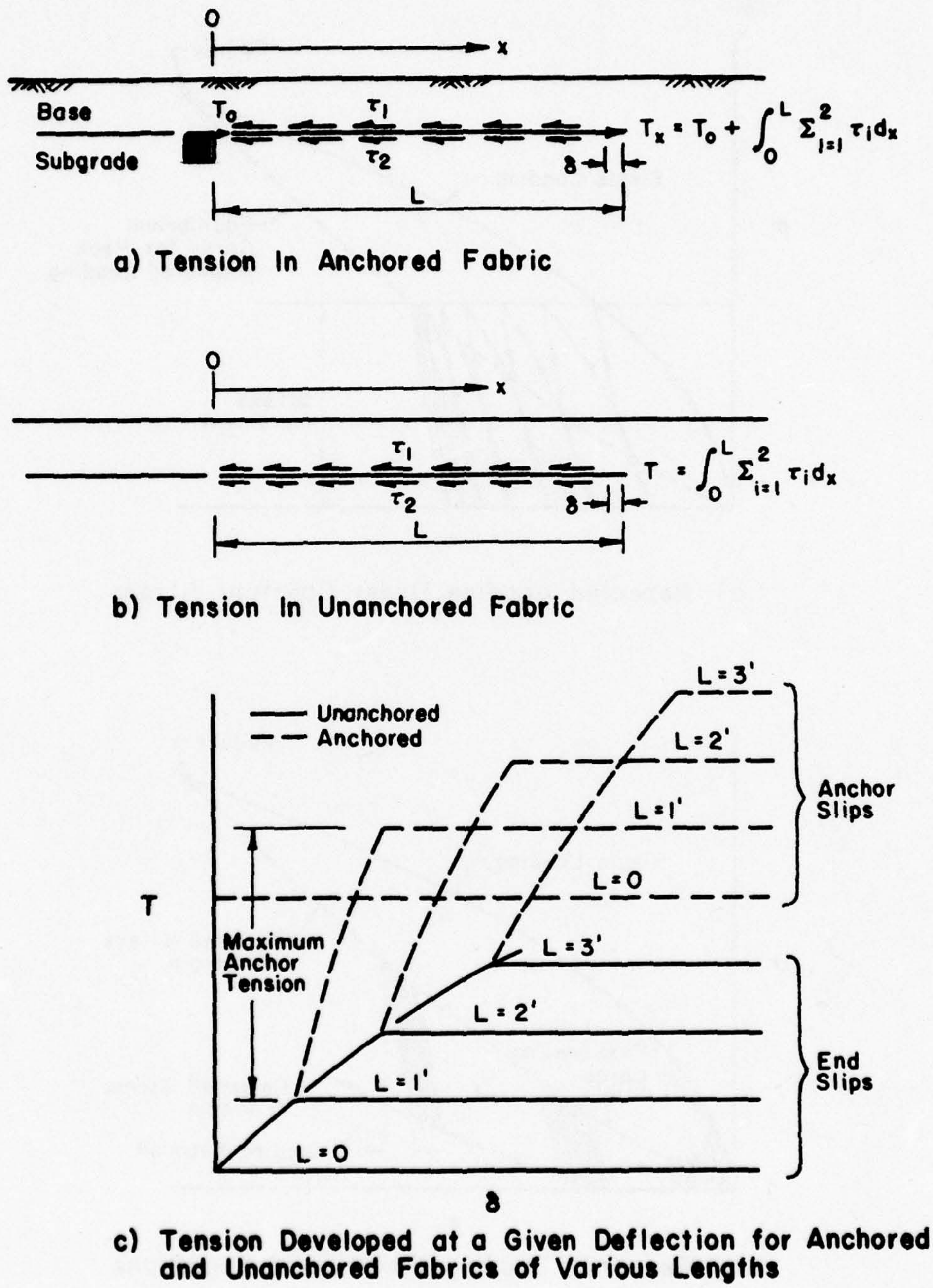
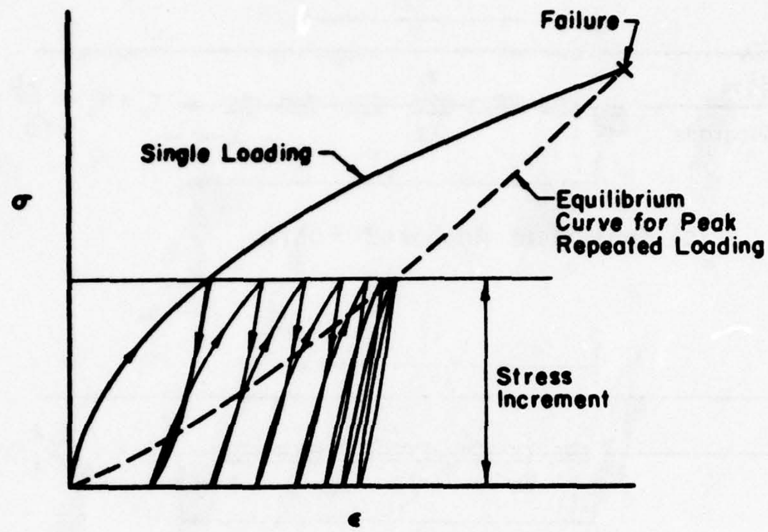
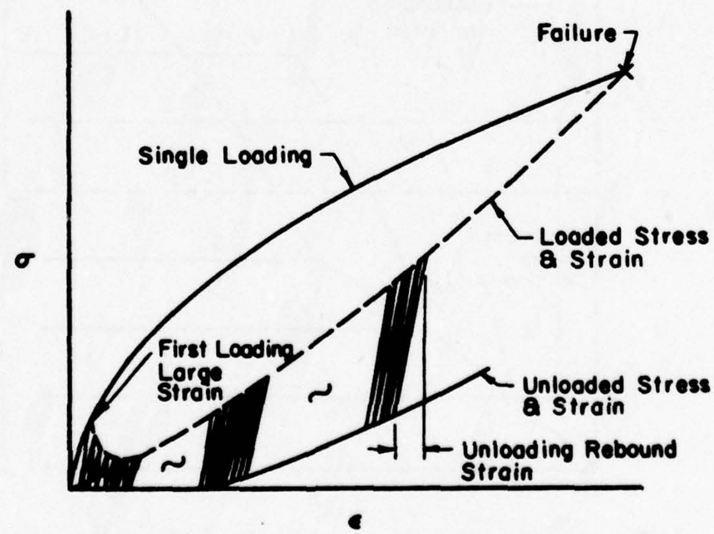


Figure 5. Effect of End Restraint on Fabric Behavior.

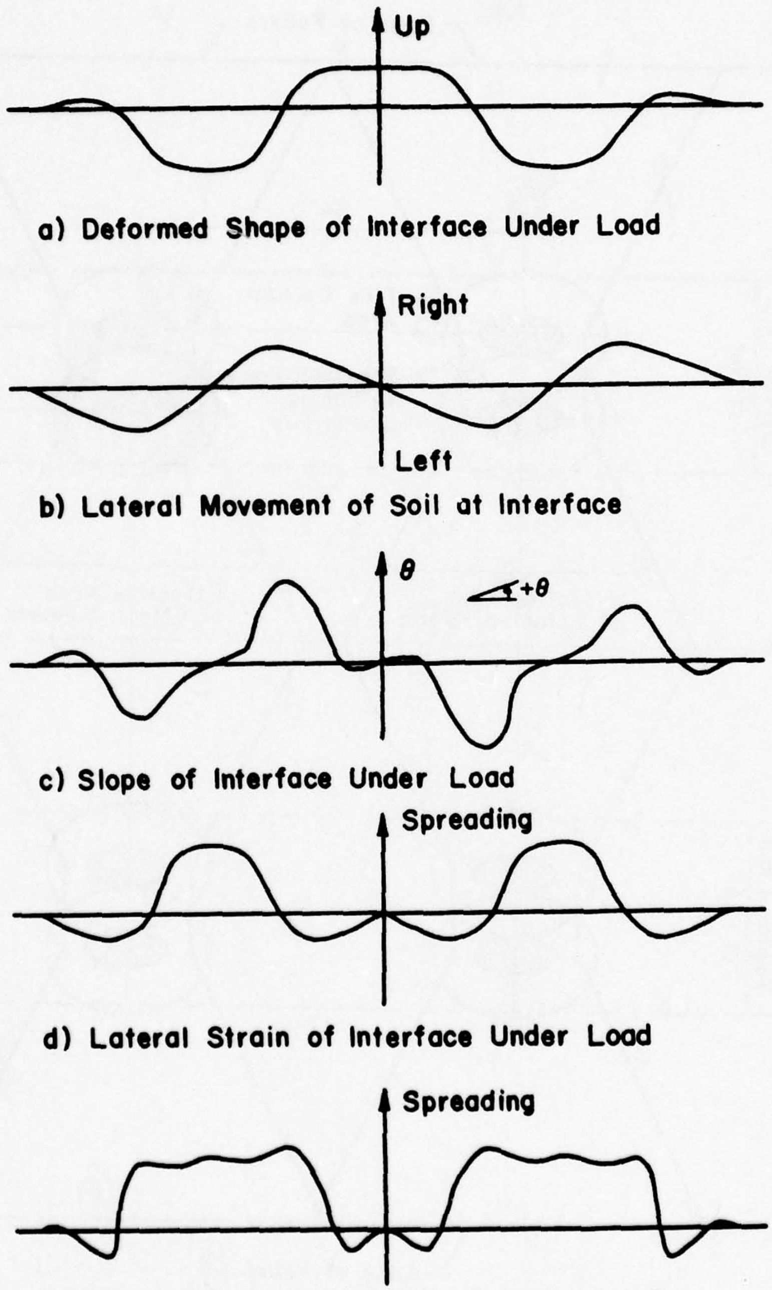


a) Repeated Loading Under Constant Stress



b) Repeated Loading Under Field Conditions

Figure 6. Typical Stress Strain Relationships Assumed for Monotonic and Repeated Loading of Fabric.



a) Deformed Shape of Interface Under Load

b) Lateral Movement of Soil at Interface

c) Slope of Interface Under Load

d) Lateral Strain of Interface Under Load

e) Strain of Interface (Fabric) Under Load

Figure 7. Strain in the Soil Parallel to Wheel Path at the Base-Subgrade Interface.

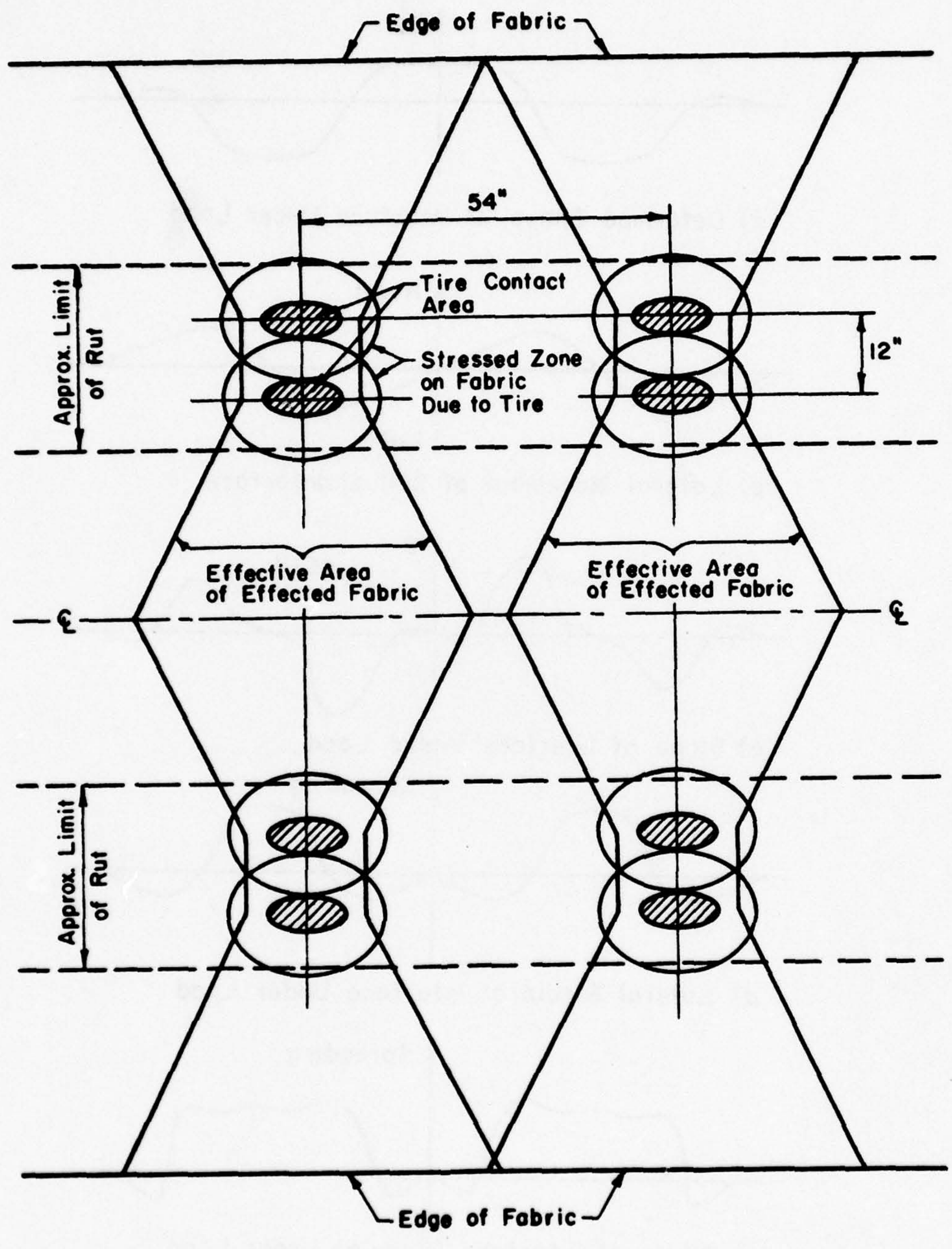


Figure 8. Assumed Stress Distribution Patterns for Dual-Tandem Loads.

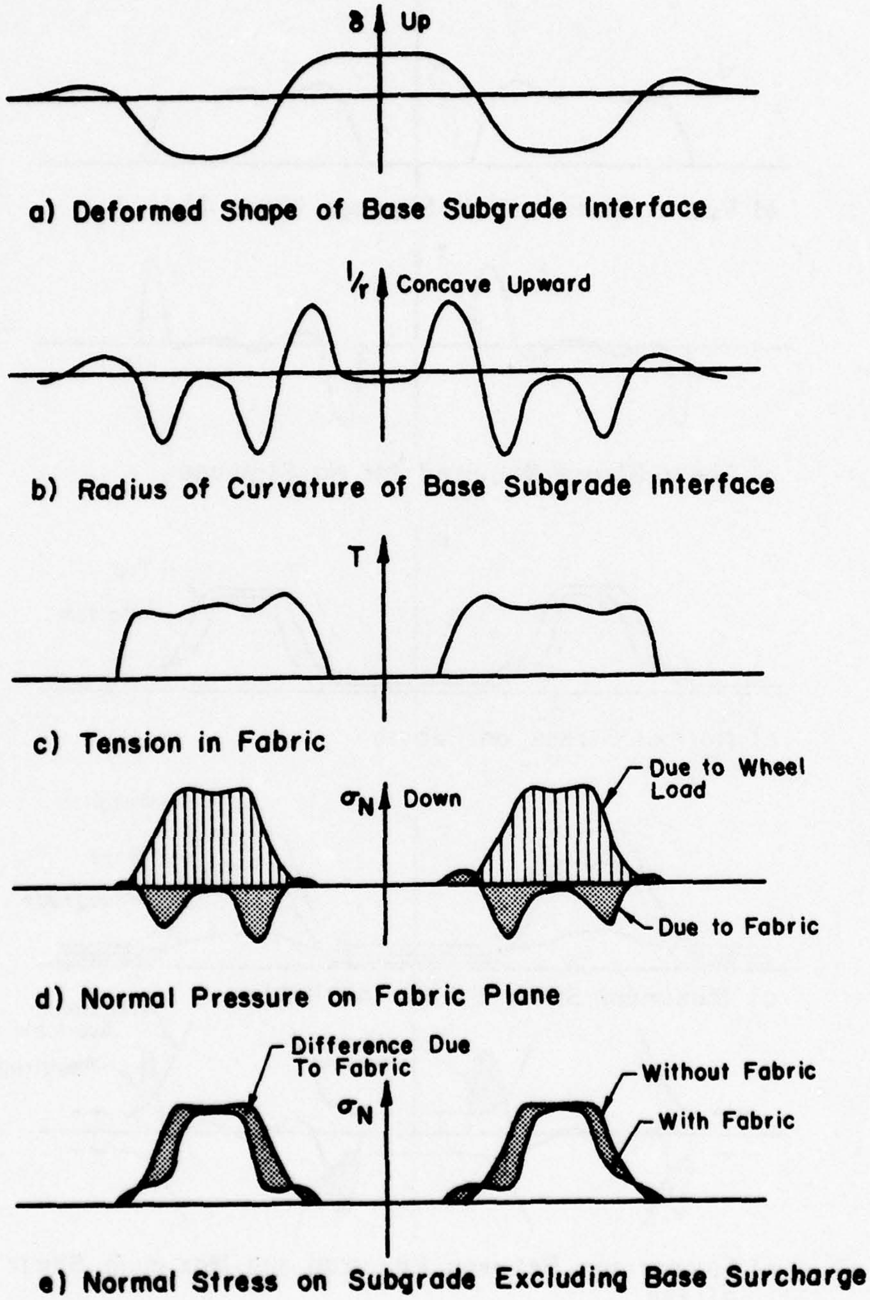
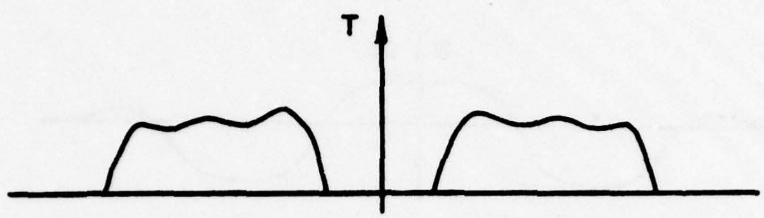
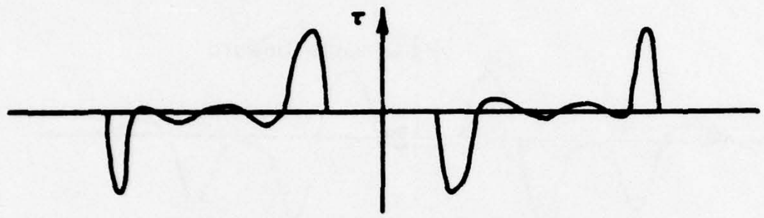


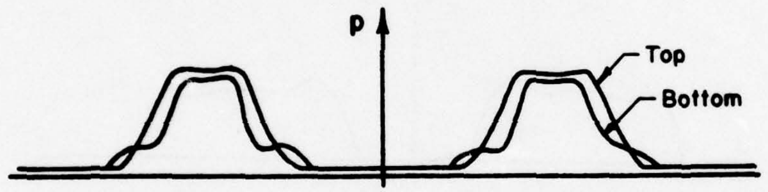
Figure 9. Effect of Normal Stress on the Subgrade Stress - Case I.



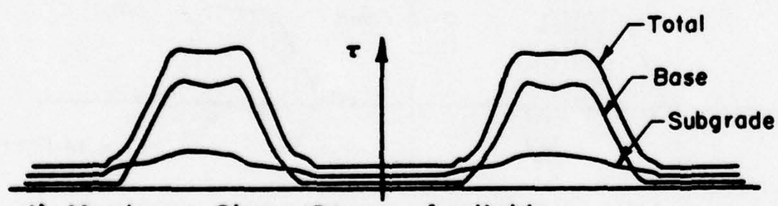
a) Fabric Tension If No Slippage (Case I)



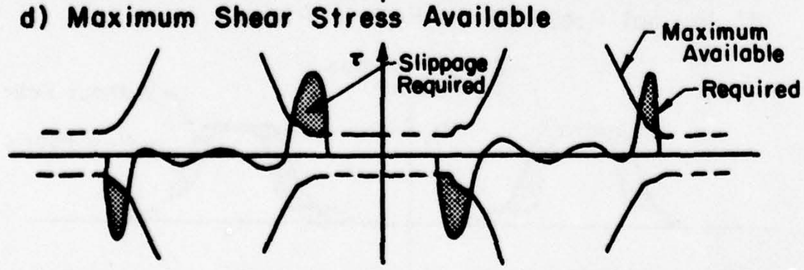
b) Shear Stress Required for No Slippage



c) Normal Stress on Fabric



d) Maximum Shear Stress Available



e) Comparison Between Required and Maximum Shear Stress

Figure 10. Analysis of Conditions for Internal Slippage of Fabric.

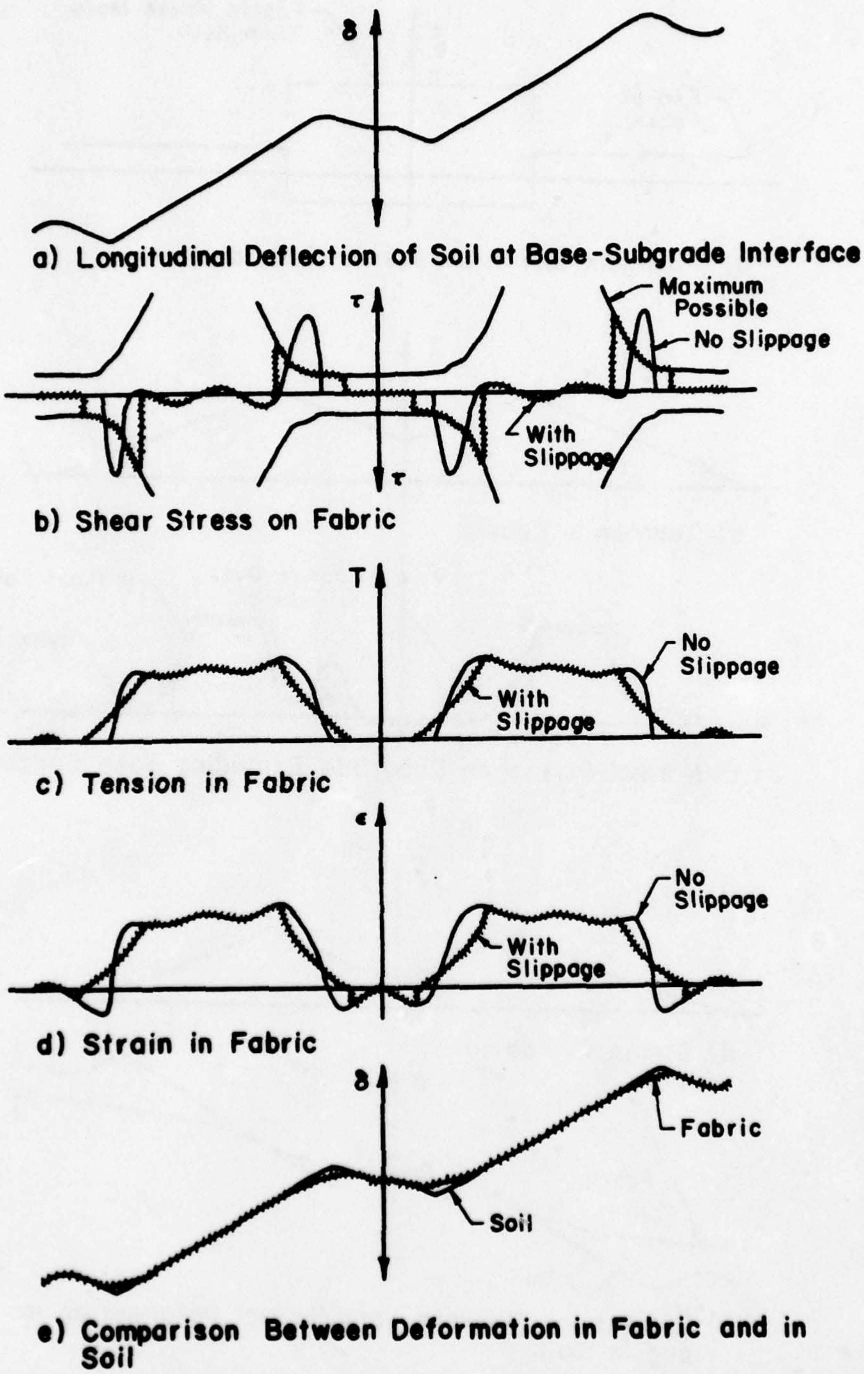


Figure 11. Soil-Fabric Compatability.

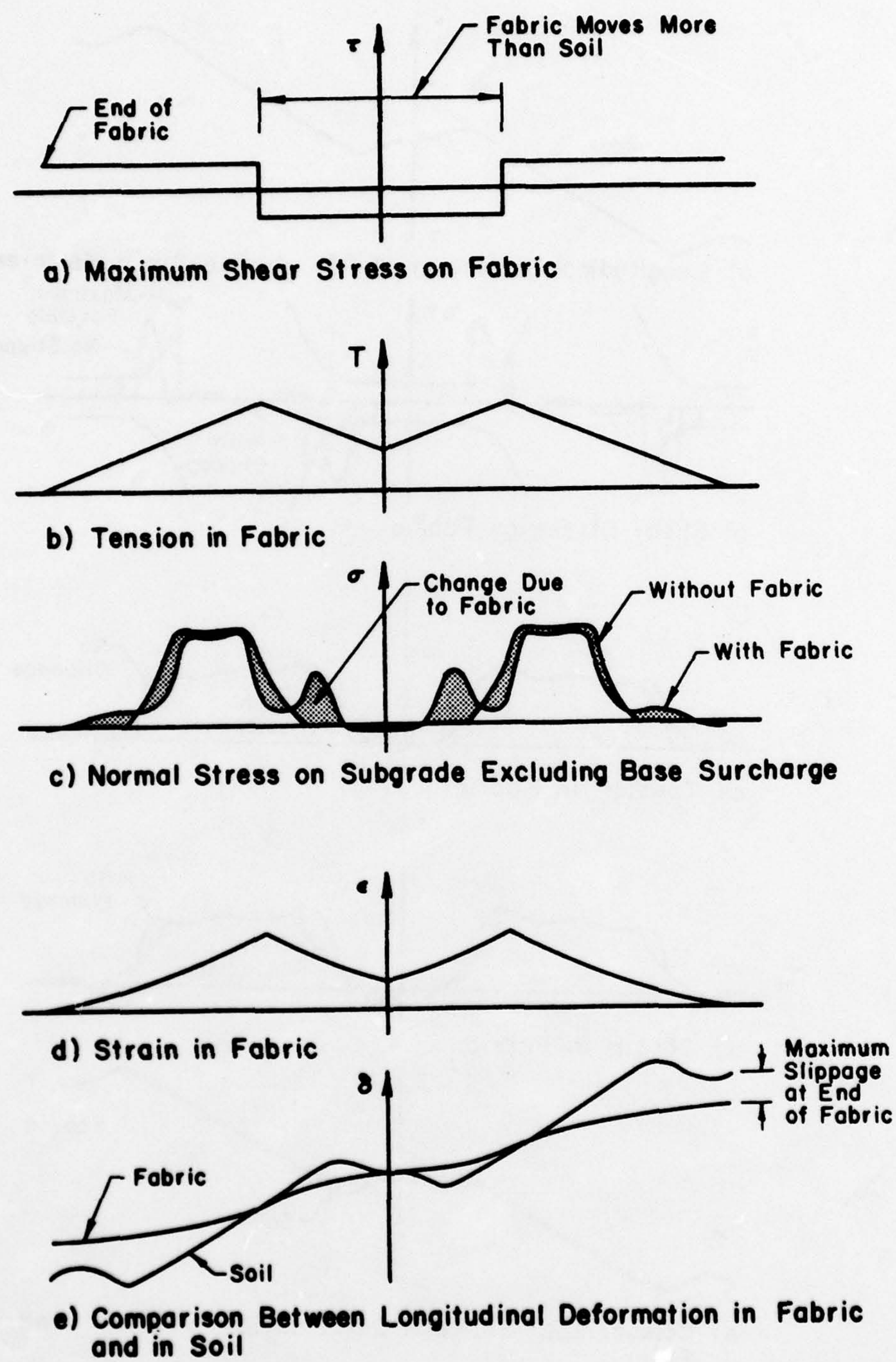


Figure 12. Effect of Normal Stress on Fabric on the Subgrade Stress - Case III.

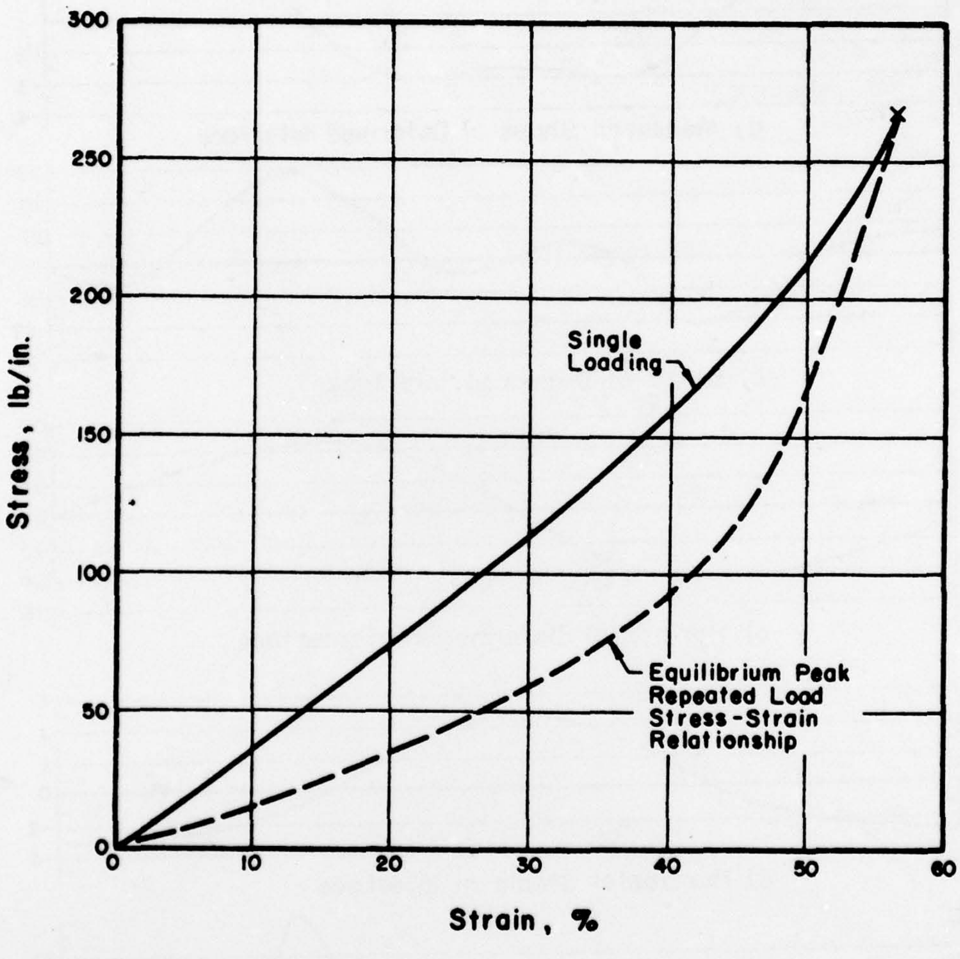


Figure 13. Stress-Strain Relationship for "Bidim" Fabric Used in Item 6.

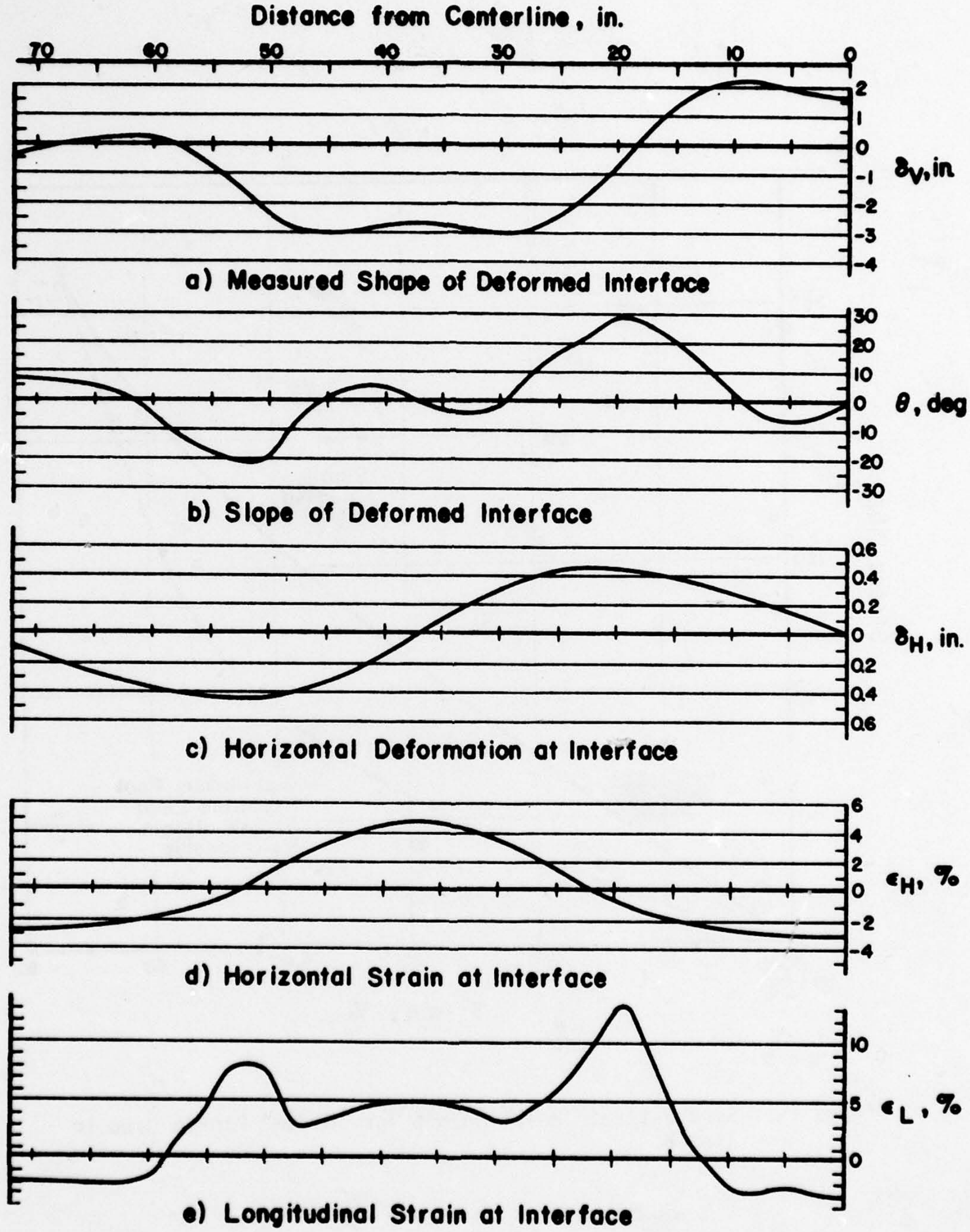


Figure 14. Longitudinal Strain at Base-Subgrade Interface, Bidim Fabric Item 6 - West Wheel Path.

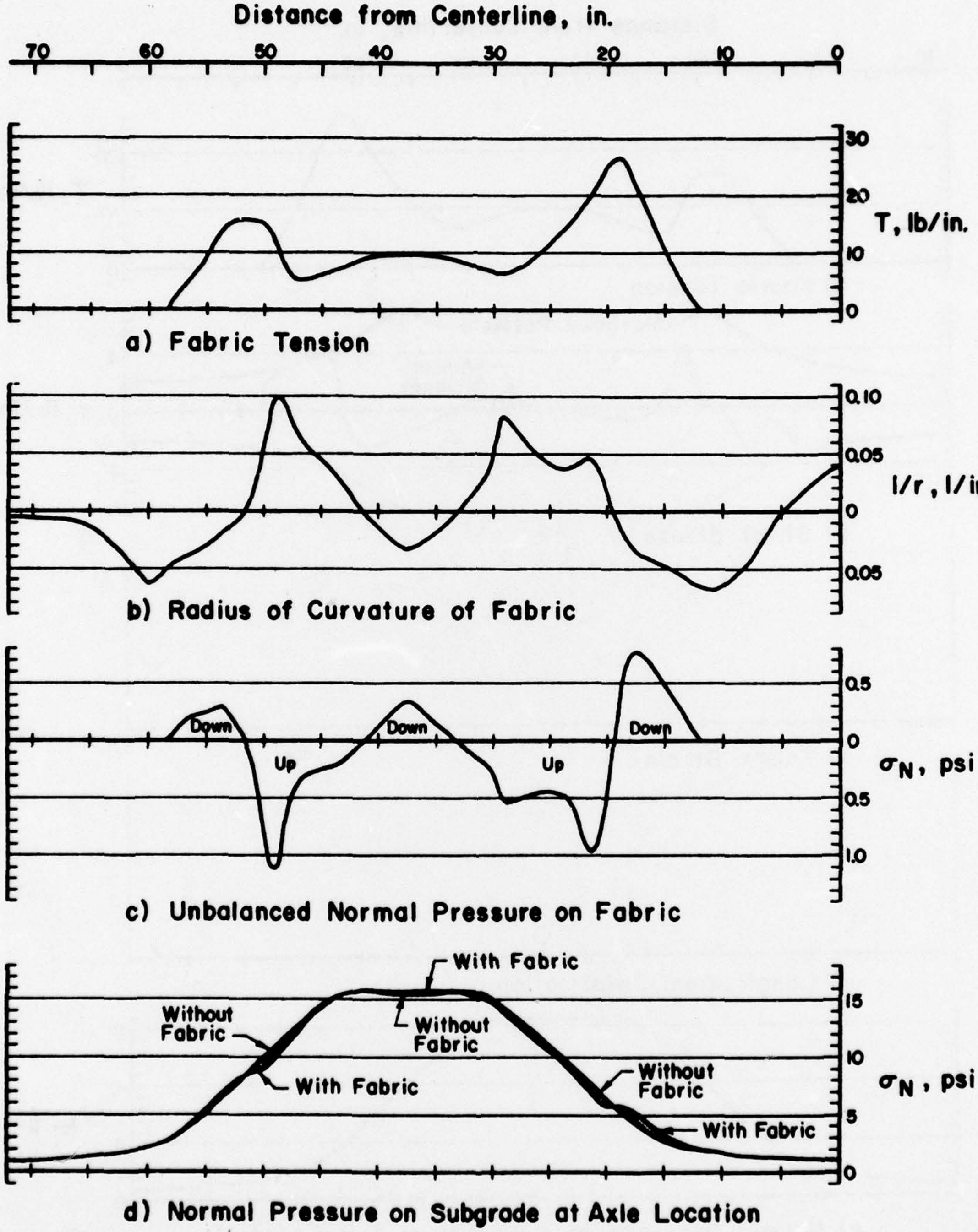


Figure 15. Effect of Normal Stress on Bidim Fabric - Case I No Slippage Item 6 - West Wheel Path.

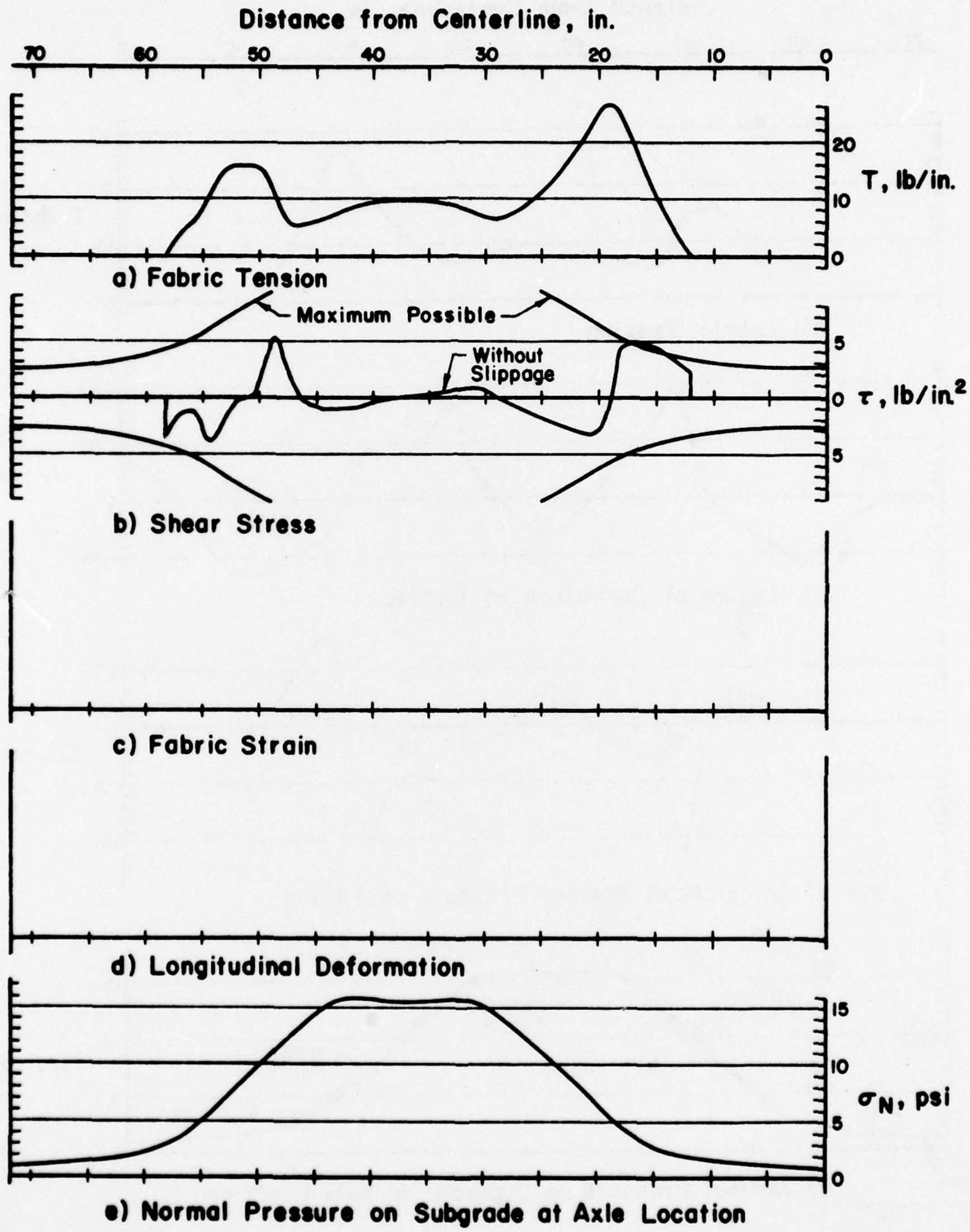


Figure 16. Effect of Normal Stress on Bidim Fabric - Case II Interior Slippage Item 6 - West Wheel Path.

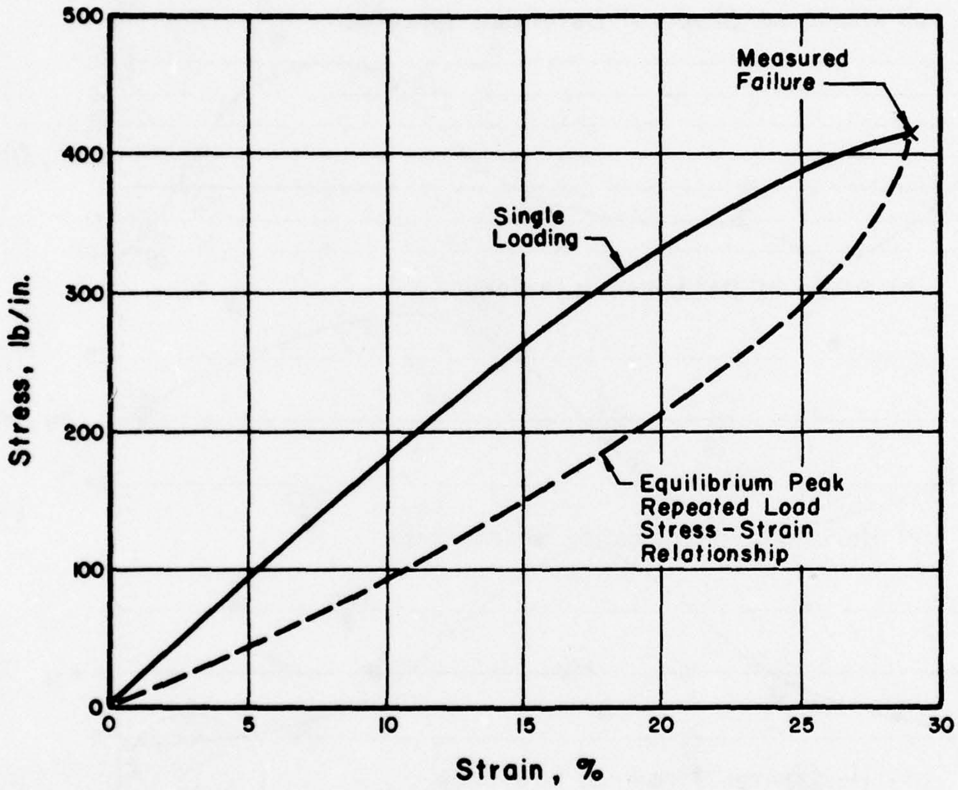


Figure 17. Stress-Strain Relationship for T-16 Fabric Used in Item 7.

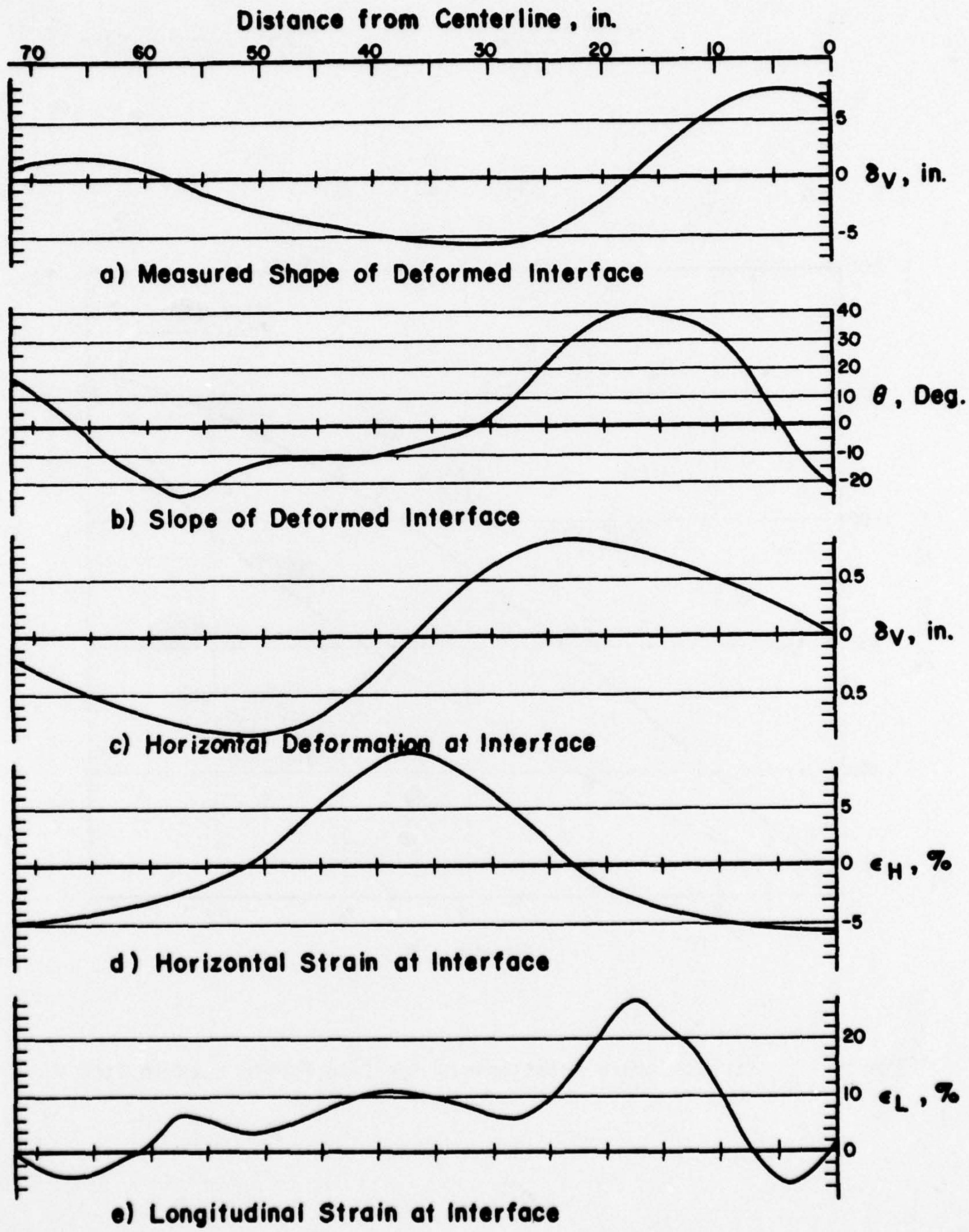


Figure 18. Longitudinal Strain at Base-Subgrade Interface T-16 Fabric Item 7 - West Wheel Path.

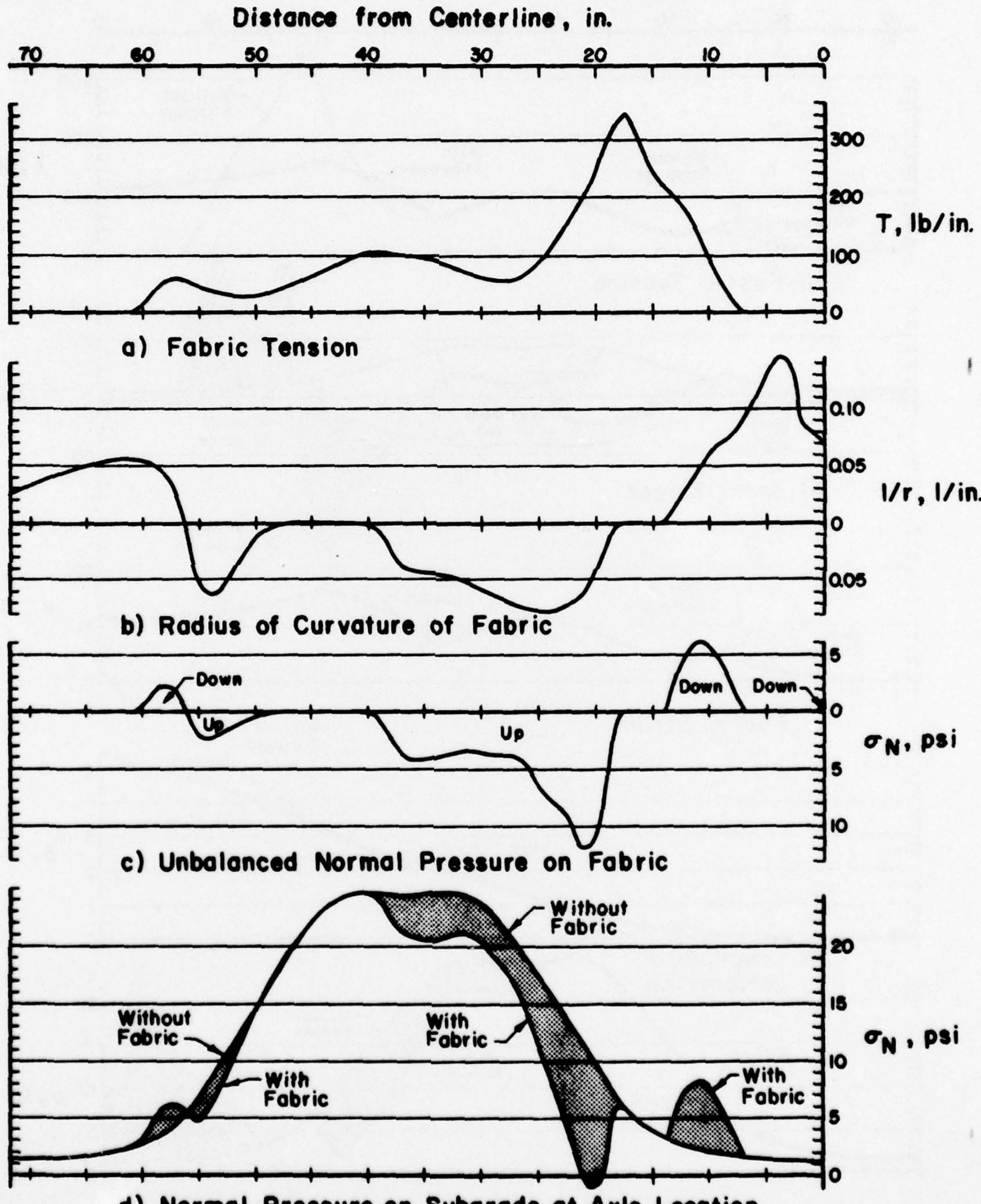


Figure 19. Effect of Normal Stress on T-16 Fabric - Case I
No Slippage Item 7 - West Wheel Path.

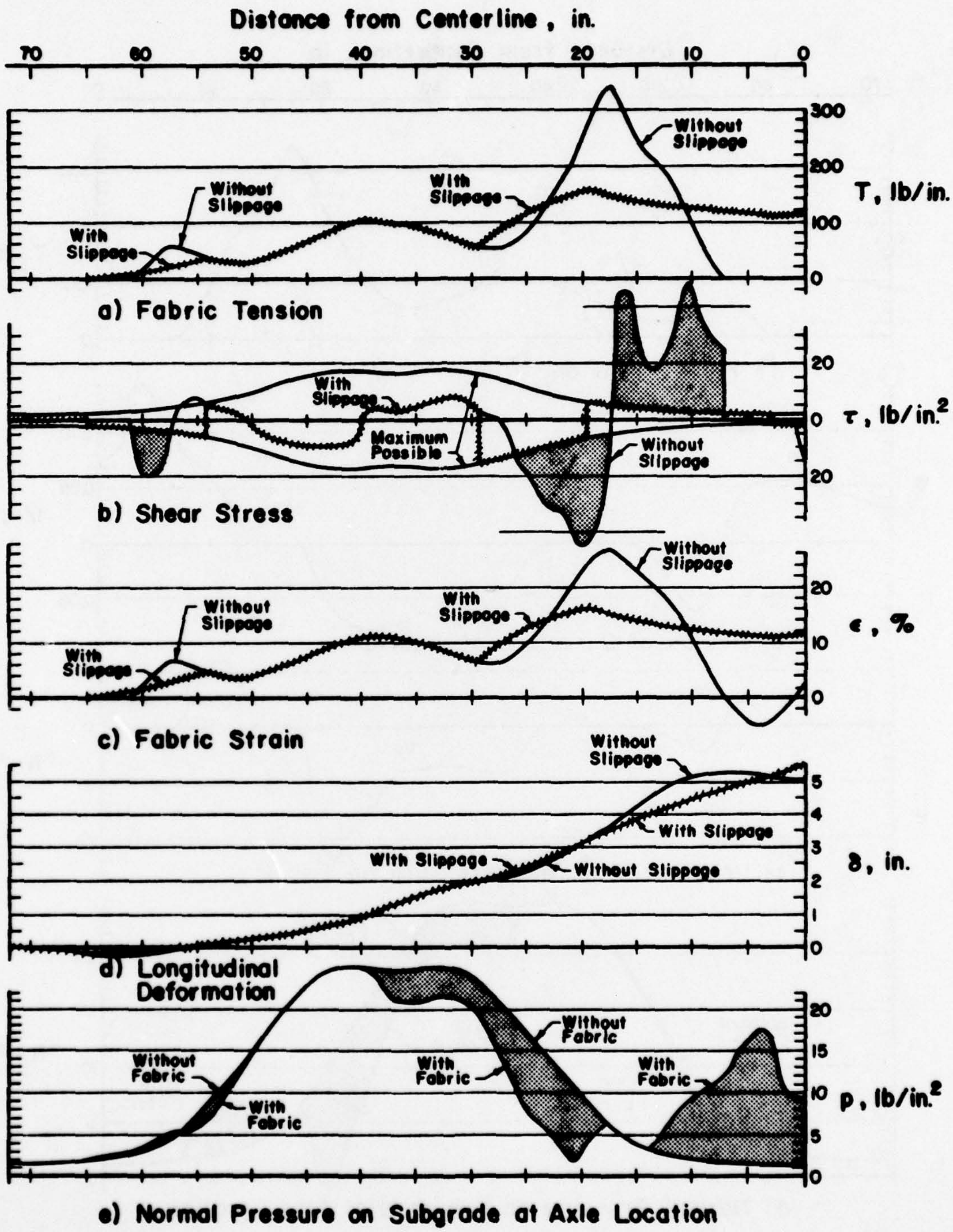


Figure 20. Effect of Normal Stress on T-16 Fabric - Case II Interior Slippage Item 7 - West Wheel Path.

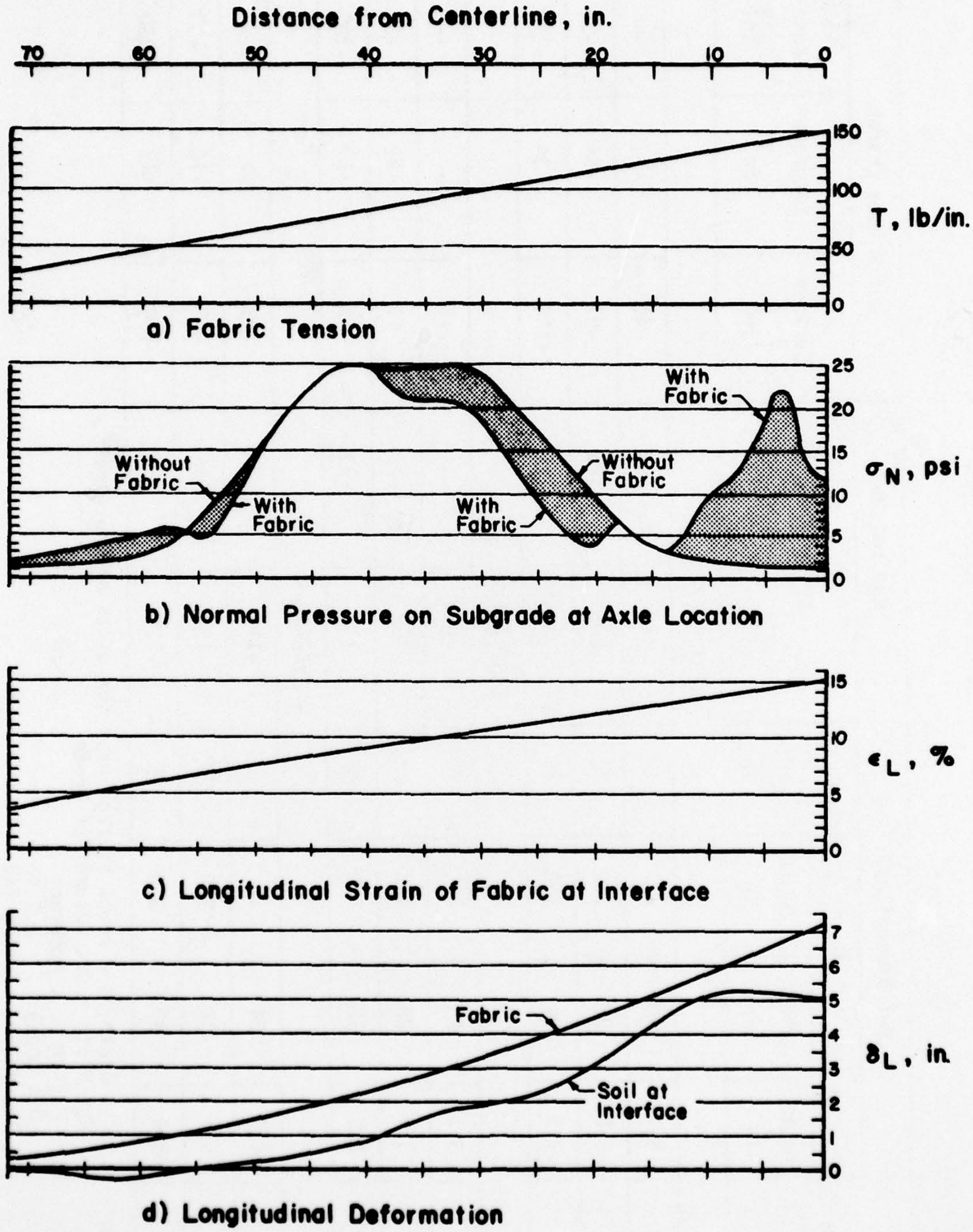


Figure 21. Effect of Normal Stress on T-16 Fabric - Case III Progressive Slippage Item 7 - West Wheel Path.

Table 1. Rut Data at Failure

Item	Rut Dimensions				Rut Volume		Net Volume Change		
	Surface		Subgrade		Surface in^3	Subgrade in^3	Surface in^3	Subgrade in^3	Base in^3
	Depth in	Width in	Depth in	Width in					
- WEST RUT -									
5	5.7	25	--		-140	-206	-45	--	--
6	6.5	32	2.7	32	-206	-86	-91	-55	-36
7	7.2	34	5.0	30	-243	-150	-164	-34	-130
- EAST RUT -									
5	3.7	23	--		-85	--	-1	--	--
6	3.7	28	1.2	22	-102	-27	+1	+32	-31
7	3.5	32	1.0	20	-112	-20	-52	+57	-109
- AVERAGE -									
5	4.7	24	--		-112	--	-23	--	--
6	5.1	30	2.0	27	-154	-56	-45	-12	-33
7	5.4	33	3.0	25	-178	-85	-108	+12	-120

Notes:
1. Rut Depth is a rough average over the width of the wheels.
2. Rut Width = Rut Volume/Rut Depth
3.

Item	Accuracy
Rut Depth	$\pm$ 0.2 in
Rut Volume	$\pm$ 20 in^2

Table 2. Surface Rut Data

Item	Coverages	Volume in^3/in	Depth in	$\frac{Volume}{Depth}$ in^2/in	Average
- WEST RUT -					
5	60 100 200	35 48 140	1.5 2.3 5.7	23 27 24	23
6	500 2,500	121 206	4.5 6.5	27 32	30
7	500 11,500 54,000	45 98 243	1.8 3.0 7.2	25 33 34	31
- EAST RUT -					
5	60 100 200	34 50 85	1.3 2.1 3.7	26 24 23	24
6	500 2,500	69 102	2.8 3.7	25 28	26
7	500 11,500 54,000	45 68 112	1.5 2.4 3.5	30 28 32	30
- AVERAGE -					
5	60 100 200	-- -- --	-- -- --	-- -- --	24
6	500 2,500	-- --	-- --	-- --	28
7	500 11,500 54,000	-- -- --	-- -- --	-- -- --	30

In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Kinney, Thomas C
  The mechanisms by which fabrics stabilize aggregate layers on soft subgrades / by Thomas C. Kinney, Ernest J. Barenberg, Champaign, Illinois. Vicksburg, Miss. : U. S. Waterways Experiment Station ; Springfield, Va. : available from National Technical Information Service, 1979.
  v, 55 p. : ill. ; 27 cm. (Miscellaneous paper - U. S. Army Engineer Waterways Experiment Station ; GL-79-5)
  Prepared for Office, Chief of Engineers, U. S. Army, Washington, D. C., under Contract No. DACA39-77-M-0257; Project No. 4A161102AT22, Task 02, Work Unit 008.
  References: p. 32.

1. Aggregates. 2. Fabrics. 3. Membranes (Road). 4. Pavement design. 5. Soft soils. 6. Subgrades. 7. Trafficability. I. Barenberg, Ernest J., joint author. II. United States. Army. Corps of Engineers. III. Series: United States. Waterways Experiment Station, Vicksburg, Miss. Miscellaneous paper ; GL-79-5.
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